APPENDIX D

ADVANCE

**Advanced Driver and Vehicle
Advisory Navigation Concept**

Traffic Related Functions
Evaluation Report (4 of7)
Documents # 8460.00

CONTAINS:

Prepared by
University of Illinois-Chicago
Urban Transportation Center

DISCLAIMER

ADVANCE Evaluation
Travel Time Prediction and Performance of Probe and Detector Data

Ashish Sen, Siim Soot, Xin Tian
and Helen Condie

URBAN TRANSPORTATION CENTER
University of Illinois at Chicago
1033 West Van Buren Street
Suite 700 South
Chicago, Illinois 60607

September 1996

Executive Summary

During the summer of 1995 eight to fifteen vehicles per day were deployed to examine the performance of the travel-time prediction (TTP) algorithm. Two study routes comprising a total of thirteen links were driven. Two of the three links with volume-occupancy detectors were selected for detailed examination. TTP estimates and probe reports were also compared on two links which did not have detector data. In the detectorized and non-detectorized cases one of the links we focused on was highly congested during the peak period while the other experienced less congestion. This provides a mix of information and conditions which provides a reasonable overview of the TTP algorithm.

Both detector and probe data performed well during the off-peak period. During the peak period the occupancy detectors quickly became saturated and yielded unreliable travel-time predictions. The probe-based predictions were better but during the peak periods substantially underestimated actual travel times. This reflects the decision made in the development of the algorithm (to use a conservative algorithm) and this study suggests that the algorithm be adjusted to reflect these underestimations. In a subsequent deployment this adjustment can be made and the algorithm will produce more accurate predictions. The present algorithm, however, performs exceptionally well when there are a few outliers among the travel times recorded during a five-minute study interval. These aberrations are largely ignored by the TTP, as indeed they should be. Lastly, the number of probe reports during five-minute intervals represent the input to the TTP process and intervals with four and more probe reports are examined to determine the effect on travel-time prediction of randomly decreasing the number of probe reports. This analysis suggests that in most instances three probe reports are adequate to provide reasonable TTPs. With an increasing number of probe reports beyond three the TTPs change very little.

Contents

List of Figures

List of Tables

1 Introduction

This report summarizes an evaluation of the quality of output received from the Travel-Time Prediction (TTP) Algorithm. In basic terms, the algorithm uses probe (vehicle) and detector data, as run through several sub-processes, to develop travel-time predictions for specific links and for specific time intervals. The overall TTP process uses the results of several other procedures which provide it with the necessary data inputs.

In practice, the Traffic Information Center (TIC) accumulates probe and detector data for a five-minute period, having obtained the probe data via RF from probe vehicles. The TIC uses these data to estimate the current travel time as well as the five-minute travel-time predictions (TTPs) for the next fifteen minute period, using an algorithm constructed as part of TRF.

In this report we evaluate the current *estimates as* well as the TTPs. The current estimates are constructed using an algorithm in Data Fusion and the TTPs are constructed using algorithms in the TTP task.

This report compares the TTPs with individual probe reports and with five-minute travel-time means. The report first presents the results of analysis using probe data only then using detector data only and finally focuses on the TTP output using both detector and probe data. In the evaluation using probe-data only the level of probe input is randomly decreased to determine how the quality of TTPs deteriorates with decreasing probe input.

2 TTP Algorithm

2.1 Background

This report concerns an evaluation of the performance of the TTP algorithm in predicting link travel times, and does not present an enhaustive explanation of the algorithm, which has been documented elsewhere (see Liu and Sen, 1995). This section will introduce the reader to the algorithm, its objectives, and its components. The TTP procedure is shown in Figure 1. While the figure (taken from the report referenced above) as shown indicates that the entire TTP process includes Outbound Broadcast Prioritization, this additional process will not be implemented and is therefore not discussed further in this document.

TTP is a dynamic process in which travel-time estimates for specific links and time periods are constructed using processed data; this procedure is differentiated from a static procedure. When fully developed, the Mobile Navigation Assistant (MNA) will contain a database of expected link travel times called Static Profiles (SP) for each time period. These estimates are the basis on which the MNA makes the calculations for expected trip travel times. TTP acts as a comparison to these fixed numbers. As probes traverse the links, the MNAs and detectors (if the link is detectorized) constantly feed data to the TIC which then processes that data into estimated link

INPUT DATA

TIC Active Data	TRF Static Profile	TRF Data Fusion	TRF Incident Detection

ON-LINE TRAVEL-TIME PREDICTION (TTP) PROCEDURE

Travel-Time Prediction
for Road Closures

Travel-Time Prediction
in the Presence of Incidents

Travel-Time Prediction
in the Absence of
Road Closures and Incidents

Outbound

Broadcast

Prioritization

OUTPUT

TRF Data: Link Travel-Time Predictions (Archived)	TIC Active Data: Link Travel-Time Updates (Broadcast)

Figure 1: Data Flow of Travel-Time Prediction in ADVANCE

travel times (see Section 2.2). The final output of these procedures is then compared to the SP expected travel time. If the actively-determined travel time differs from the static profile by more than twenty seconds, the TTP program overrides the SP and uses the actively-determined travel-time estimate to determine the most efficient route. In essence, TTP enables the MNA to propose the most efficient route under current travel conditions, using both static and dynamic estimates. Note that data fusion is only performed if the link under question is detectorized; if it is not, detector travel time conversion (DTTC) cannot be performed and the active travel-time estimate is based on probe data alone.

2.2 Data Inputs

An overview of the process by which TTPs are computed is shown in Figure 2. If a link is detectorized, fused data based both on detectors and probes are used in the TTP process — or in estimating the current travel-time estimates. If a link is not detectorized, probe data alone are used. Either way, static profiles (which are essentially averages over different days of link travel times) are subtracted from these estimates and the differences are broadcast if their absolute value exceeds 20 seconds and if no incidents or road closures are indicated. In the ADVANCE design a more complex method was described in order to determine which differences were to be broadcast; this method was not appropriate for targeted deployment and the 20-second rule just mentioned was used instead. If an incident flag is 'on' or if there is road closure then the TTP minus static estimate times are not broadcast. Instead, other estimates obtained from ID (Incident Detection) under incident conditions, or in the case of known lane or road closures, are broadcast.

While in the actual deployment of ADVANCE, for each time period, each link and each forecast period (current, 5, 10 or 15 minutes into the future) a single time estimate is generated, in this evaluation we take advantage of a very rich data source to ask a number of 'what if' questions. In particular, we ask the following questions:

- How good are travel-time estimates when detector data is not available and only probe data is used?

- How good are travel-time estimates when no probes are available and only detector data is used?

- How good are travel-time estimates when fused probe and detector data is used?

- What is the effect of using different numbers of probe reports per time interval when only probe data is used?
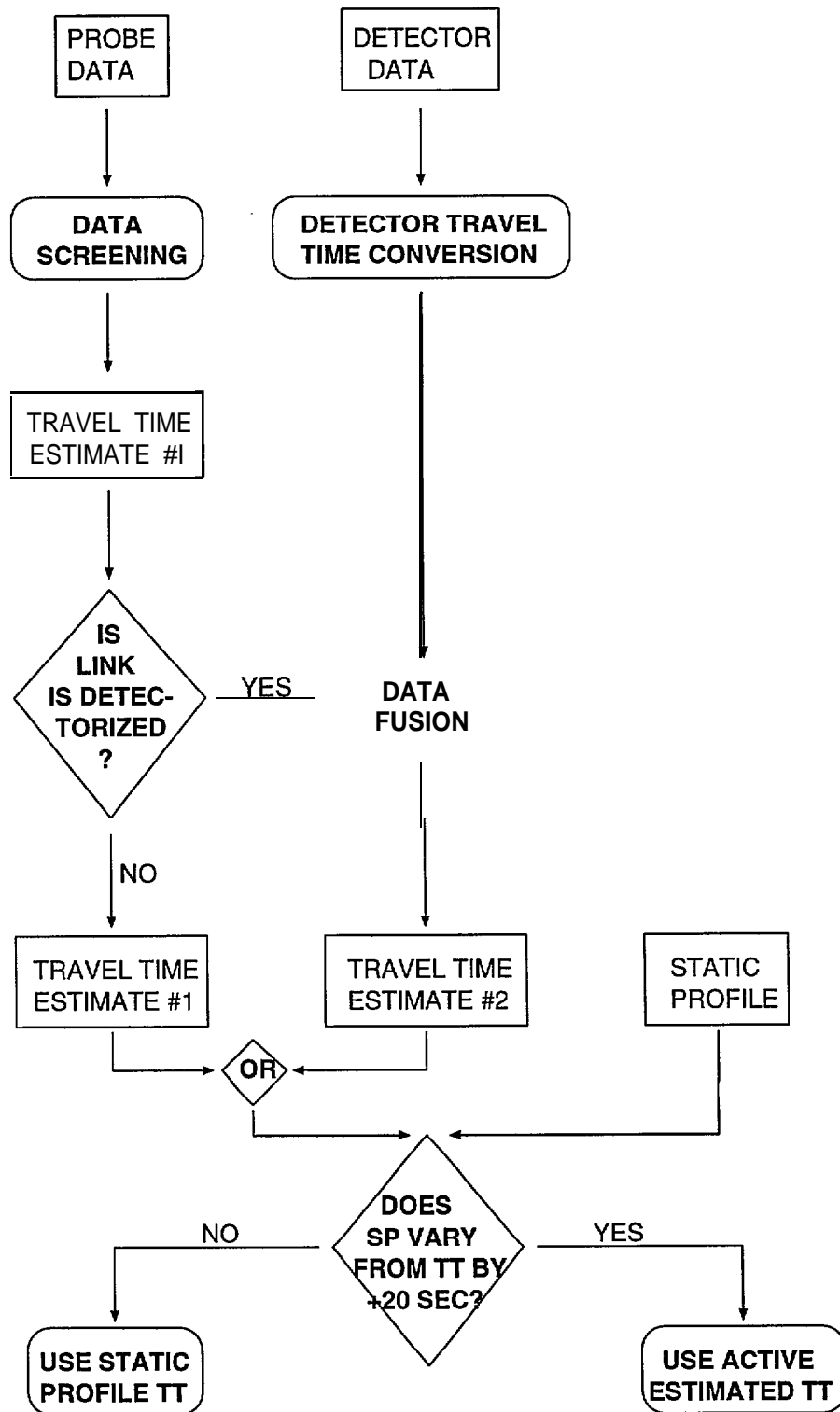
Figure 2: Data Flow of Active Travel Time Prediction in ADVANCE

2.3 On-Line TTP Procedure

The TTP algorithm is run three times, once for probe data only, once for detector data only, and the third time using the fused probe and detector data. In addition, the two runs that use probe data are run several times at Deployment Levels 1, 2, 3 and 4; the deployment level refers to the number of probe reports randomly selected and utilized to compute the average travel-time values for a given link in that five-minute interval. Five-minute intervals are used because detectors only transmit data in five-minute intervals. Both detector and probe data are assembled into five-minute intervals.

3 Data Collection and Reduction

In this section we discuss the collection of probe-vehicle data and detector data.

3.1 Probe-Vehicle Reports

Data used in the TTP processes were collected during the summer of 1995, when up to fifteen probe-equipped vehicles were driven four days a week over an eleven-week period. During this time almost 60,000 miles were driven to produce over 50,000 link reports within a defined study area. These reports provide information on at least three critical elements of travel: travel time, congested time and congested distance. This information is computed in the vehicle in its on-board MNA and is recorded in two different ways, in the vehicle (on memory cards, which are similar to computer diskettes) and as sent by radio frequency (RF) to files tabulated at the Traffic Information Center (TIC) in Schaumburg, Illinois.

3.1.1 Data-Collection Routes

Data were collected on several study routes from June 5th to August l0th, Monday through Thursday. The original ADVANCE project design called for a massive probe deployment covering scores of routes with thousands of cars. This original version was scaled back; the overall evaluation uses data gathered from a targeted deployment of between eight to fifteen cars per day over short, defined study routes. The evaluation of TTP uses data from a one-week period when we had at least twelve probe vehicles per day. To simulate full deployment, the probes were driven repeatedly over two short study routes, thereby creating for each link a database of commensurate size to that of the original design. The entire routes driven on Dundee Road and adjacent arterials are within the municipality of Wheeling, Illinois (north suburban Chicago). Dundee Road was selected for the routes because it carries a high volume of traffic and because each signalized intersection is demand actuated by loop detectors (including turning lanes). In addition to the loop detectors at signalized intersections, there are volume

and occupancy detectors on three links. Although Dundee Road extends for several miles within the greater ADVANCE study area, the number of potential places along Dundee Road where the necessary field tests could be performed was very limited. However, because Dundee Road is the only arterial within the ADVANCE test area with detectorized links sending data to the TIC, these restrictions were accepted.

The data-collection routes also required a convenient location where vehicles could turn around safely and avoid being off the study route for a long period of time. In addition, the routes needed a mix of link and intersection characteristics. The presence of detectors and the mix of link types are both necessary to the procedures used in the TTP algorithm. Alternative study routes were either too short or too long or did not have the desired mix of link types.
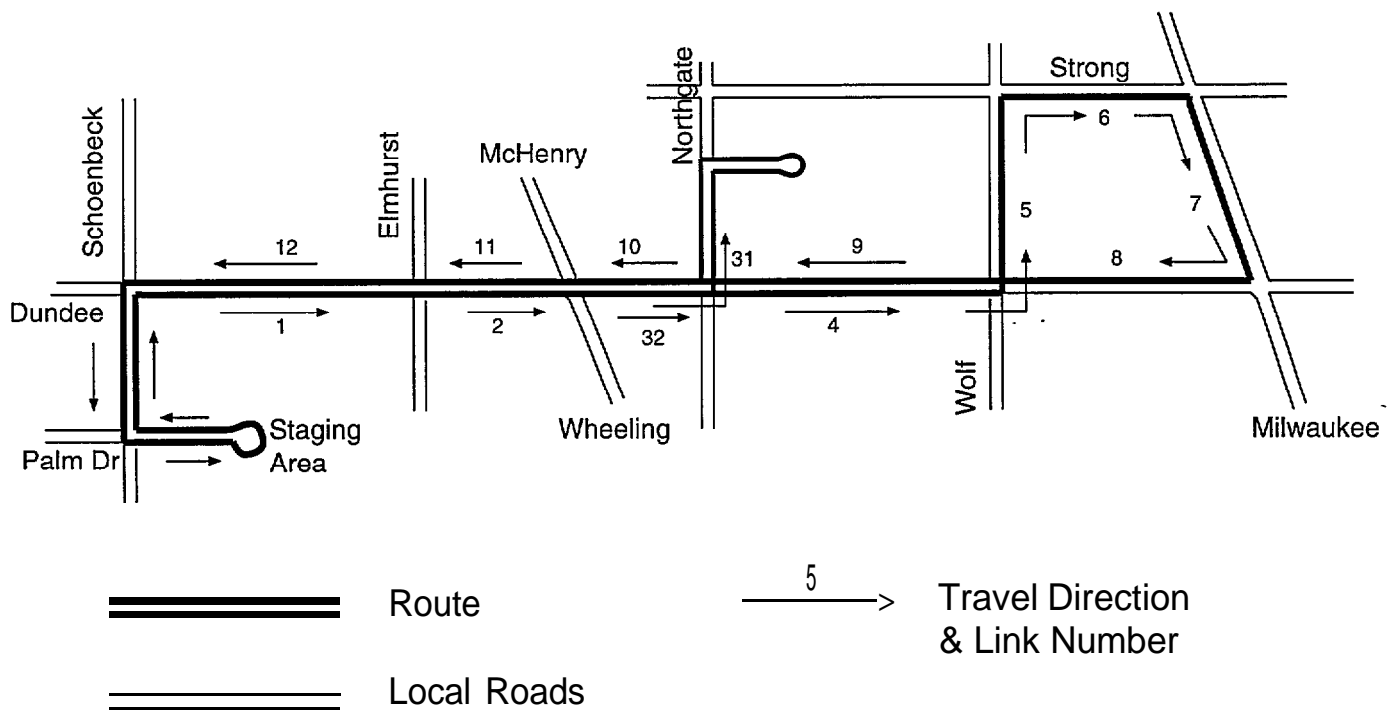
Figure 3: Probe-Data Collection: Dundee Road Routes

Probe data used in the TTP procedure were collected along the two routes depicted in Figure 3. The longer 12-link route, which extends to Milwaukee Avenue in the east, was designed to be completed within a fifteen-minute period. During the off-peak time period most drivers completed the route in ten to fourteen minutes. During the peak period this route proved to be too long to complete in fifteen minutes and a shorter alternative was used. This route includes the left turn on Link 31 onto Northgate where drivers were able to turn around and proceed to Link 10. Thus, with twelve cars on the road (on average) these routes would yield one link report per minute and five reports per five-minute interval.

The section of the route on Schoenbeck Road and Palm Drive (near the west end)

was used as a staging and turnaround area; since it was too short to complete a recognized link, data were not collected for this section of the route.

The first seven weeks of data collection (June 5-July 20) consisted of driving on these two set routes. After that period, data were additionally collected from other routes, within the same area, to allow an analysis of turning relationships. Table 1 shows the number of probe reports recorded for each day of data collection. The evaluation which is the subject of this report only concerns those data collected on the Dundee Road routes (see Figure 3), during the week beginning July 17. It may be seen from Table 1 that the week beginning July 17 provides the largest number of probe reports.

3.1.2 Data-Collection Schedule

At the beginning of each day of data collection, a twelve-noon briefing was held at the ADVANCE office in Schaumburg. At this time the drivers were assigned vehicles and they left the office at approximately 12:30 pm. Data were collected by probe vehicles driven in the study area between 1:00 pm and 7:00 pm, with breaks as described below.

On each day of data collection a field manager was present at the staging area. The field manager ensured that vehicles were driven on the study routes at satisfactory headways and instructed drivers when to take breaks.

The drivers were given a ten-minute break from approximately 2:00 pm to 2:10 pm and another one from approximately 6:00 pm to 6:10 pm. Each driver took his or her break at a slightly different time, as each was dispatched by the field manager to the break area as they arrived at the staging area. During breaks each probe vehicle was inactive for more than ten minutes as time was lost off-route and also while the vehicle and MNA warmed up. The longest break occurred from 3:30 pm to 4:00 pm. After this break, during the two-hour peak period from 4:00 pm to 6:00 pm, the drivers operated their vehicles without scheduled breaks.

3.1.3 Data Processing and Reduction

Data received from probe-vehicle MNA reports were reformatted to retain only the information needed for this evaluation and only that data from the links seen in Figure 3. Information manually collected by probe drivers concerning incidents was then added to the probe-report database. Finally, the data were comprehensively reformatted into a form chosen to facilitate analysis.

Table 1: Probe Reports for each day of Data Collection

Date	No of Reports	Percent of Total
6/05	660	1.3
6/07	395	0.8
6/08	1140	2.3
6/12	1382	2.7
6/13	1712	3.4
6/14	1014	2.0
6/15	446	0.9
6/19	1178	2.3
6/20	1591	3.1
6/21	1503	3.0
6/22	2372	4.7
6/26	2037	4.0
6/27	1481	2.9
6/28	1744	3.4
6/29	1546	3.1
7/05	1560	3.1
7/06	1996	3.9
7/10	1689	3.3
7/11	1282	2.5
7/12	1507	3.0
7/13	1046	2.1
7/17	2285	4.5
7/18	2252	4.4
7/19	2140	4.2
7/20	1901	3.8
7/24	880	1.7
7/25	907	1.8
7/26	1017	2.0
7/27	899	1.8
7/31	949	1.9
8/01	1069	2.1
8/02	1038	2.1
8/03	1139	2.3
8/04	949	1.9
8/07	1058	2.1
8/08	1050	2.1
8/09	873	1.7
8/10	933	1.8
Total	50,620	100.0

3.2 Detector-Data Reports

TTP also makes use of detector data, which are gathered from in-road loop detectors located along the data-collection routes. For a comprehensive discussion of how these data are processed by the Detector Travel-Time Conversion (DTTC) algorithm, see Berka et al. (1996). The following subsection is intended to act as a brief introduction to the detector data used in TTP.

3.2.1 Data Collection

As seen in Figure 3, probe-data collection took place along Dundee Road in Wheeling, Illinois. While Dundee Road has about 30 intersection approaches which can generate on-line detector data for the ADVANCE project, the routes selected for data collection contain only three detectorized links (Links 1, 7 and 11 on Figure 3). Because the data-collection exercise was designed to concentrate probes on fewer links, thereby simulating a larger deployment over a larger study area, these three detectorized links provide sufficient data for our purposes.
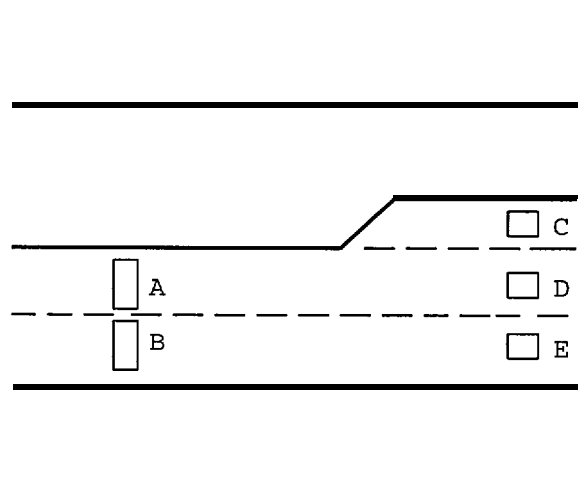
Figure 4: Location of Loop Detectors Used in Data Collection. (A through E represent in-ground detector locations.)

Two types of in-road loop detectors are present on intersection approaches on Dundee Road, which are part of two closed-loop systems. System detectors (detectors A and B in Figure 4) are located 250-300 feet upstream of the intersection and approach detectors (labeled C, D and E in Figure 4) are located just upstream of the stop line. While both types of detector measure traffic volume and occupancy, TTP only uses information from the system detectors, A and B. These two detector groups are used to actuate traffic signals, allowing for coordinated green times and continuous traffic flow along Dundee Road. Because of the presence of other arterials leading into Dundee Road, detector data also help coordinate traffic flows among these other roads.

9

Detectors are generally placed in parallel positions along a link, as seen in Figure 4.

Information is collected from system loop detectors for each closed-loop system (type Econolite KMC-10000 controllers), which begin data transmission back to the TIC. These data, along with information sent in by MNAs in the probe vehicles (transmitted to the TIC using radio frequency), constitute part of the TIC's communications subsystem. Detector data are sent at five-minute intervals. As recorded by the TIC, these data have a dual nature, and are stored in both statically and dynamically-generated formats. Data collected in this fashion are used on-line for ADVANCE project tasks such as TTP and are then archived.

3.2.2 Data Processing and Reduction

Detector data are sent in five-minute intervals to the TIC. These data are then processed on-line into usable configurations. Data for use in evaluations are then reprocessed off-line into configurations matching those of the MNA and memory-card data to allow for easy comparison. There are two basic forms for detector data: detector-by-detector and aggregated. Detector-by-detector data contain separate reports for each detector. Aggregated data are detector data aggregated over all detectors within a given group by averaging occupancy and summing the volume; this process creates a data set providing multiple reports for links at specific time stamps. DTTC, and thus TTP, uses aggregated data, which includes two values (average occupancy and total volume) derived from detectors at parallel locations on a given link.

The data are next organized into a database. As part of this process, the data are reduced to eliminate links not on the study route. Data reduced in this fashion produce a data set similar in format to Table 2, which is based on the output for August 1, 1995. Detector data are reduced to only include those links within the route shown in Figure 3, that is, Links 1, 7 and 11. For a full discussion of the Detector Travel-Time Conversion (DTTC) algorithm, see Berka et al. (1996).

Table 2: Sample of Reduced Data Output

Date m/d/yr	Time hr/min/sec	Traffic Volume vehicles per 5-minute interval	Occupancy (% of time)	Link ID (hex)	Link ID	Detector Station Name
8 1 95	13 2 27	72	16	"8cae7"	11	"DU_W_83"
8 1 95	13 2 27	60	9	"88c9a8"	7	"DU_S_MILWK"
8 1 95	13 2 27	91	25	"88cb2b"	1	"DU_E_83"
8 1 95	13 2 27	64	25	"88c9a8"	7	"DU_S_MILWK"
8 1 95	13 2 27	83	19	"88cb2b"	1	"DU_E_83"
8 1 95	13 2 27	67	6	"8cae7"	11	"DU_E_83"

4 Travel-Time Prediction

4.1 Predicted and Actual Travel Times

Every five minutes the TIC computes travel-time predictions for subsequent five-minute intervals. These predictions are evaluated by comparing them to actual travel times collected by probe vehicles for the following four time periods (where time 't' is the end of the five-minute period providing input for the algorithm):

. Current estimate (from t to t+5 minutes),

- Five-minute forecast (from t+5 to t+10 minutes),

- Ten-minute forecast (from t+10 to t+15 minutes) and

- Fifteen-minute forecast (from t+15 to t+20 minutes).

The current estimate comes from probe or fused data and pertains to the period immediately after the end of the five-minute data accumulation period. The three forecasts are products of the travel-time prediction (TTP) algorithm (see Liu and Sen, 1995). In order to differentiate between the two we will use the term estimate for the current estimate and the term forecast for the TTP output. All four are estimates.

The comparison of the probe and TTP data is not straightforward for several reasons. First, the TIC broadcasts information to the probe vehicle (MNA) only when the TTP differs from the static profile estimate by more than twenty seconds. For this reason many of the TTPs are not broadcast; we will be evaluating all of the TTPs regardless whether or not they are transmitted to the probes. Second, the MNA and the TIC use slightly different five-minute intervals. The MNA uses multiples of five in defining time intervals while the TIC uses the time at which it is first powered up, as the beginning of the first five-minute interval and therefore it is not synchronized with the MNA. Even though the MNA places the data from the TIC into its own five-minute scheme we are evaluating the performance of the TIC TTPs based on the five-minute scheme recognized by the TIC. For example, if the TIC concludes its TTP computation at 1:04 pm then we will compare its first TTP against the actual probe data from the 1:04 - 1:09 pm period and the next one for the 1:09 - 1:14 pm period.

4.2 Prediction Algorithm

A decision was made early in the development of the TTP algorithm to establish an estimating procedure which is rather conservative (defined as preferring gradual development to abrupt change). This reflects the expectation that some travel times will vary substantially from the norm and these very isolated cases should not seriously affect the forecast. High travel times in a single five-minute period or even several five-minute periods may only signify a momentary problem which can disappear as

11

quickly as it occurred. There may also be cases of motorists voluntarily stopping on the shoulder, reporting high travel times and implying congested conditions when none exist. This general phenomenon is illustrated on Figure 5. The y-axis on each plot displays the travel times and the z-axis represents the seventy-two five-minute intervals from 1:00 pm to 7:00 pm. Each individual probe travel time is plotted with the symbol * and the current estimates and five, ten and fifteen-minute forecasts with the symbol o. This convention is used throughout this paper.

Just after 5:00 pm (Interval 48) two probe vehicles reported travel times of between 500 and 600 seconds (nearly ten minutes) within the same five-minute interval. It is not important why this occurred but rather how the TTP algorithm reacted to it. These two high travel-time readings occurred just once and all the other reports before and after were within the same general range of less than one hundred seconds.

The current estimate for the five-minute period in which the high readings occurred jumped from about 60 seconds in the previous five-minute interval to 160 seconds. In the following estimate the value was down to 120 seconds and then subsequently to 80. In this case the estimate did not overreact to the two high probe reports. Had it done so it would have likely taken it a fair amount of time for the estimate to return to the more normal conditions experienced in the very next five-minute interval.

On all three forecasts the effect of these two high travel times is definitely muted. By the fifteen-minute forecast all travel-time forecasts for the time in question are less than one hundred seconds. In this special case the TTP functioned particularly well. A more complete evaluation follows in the next section.
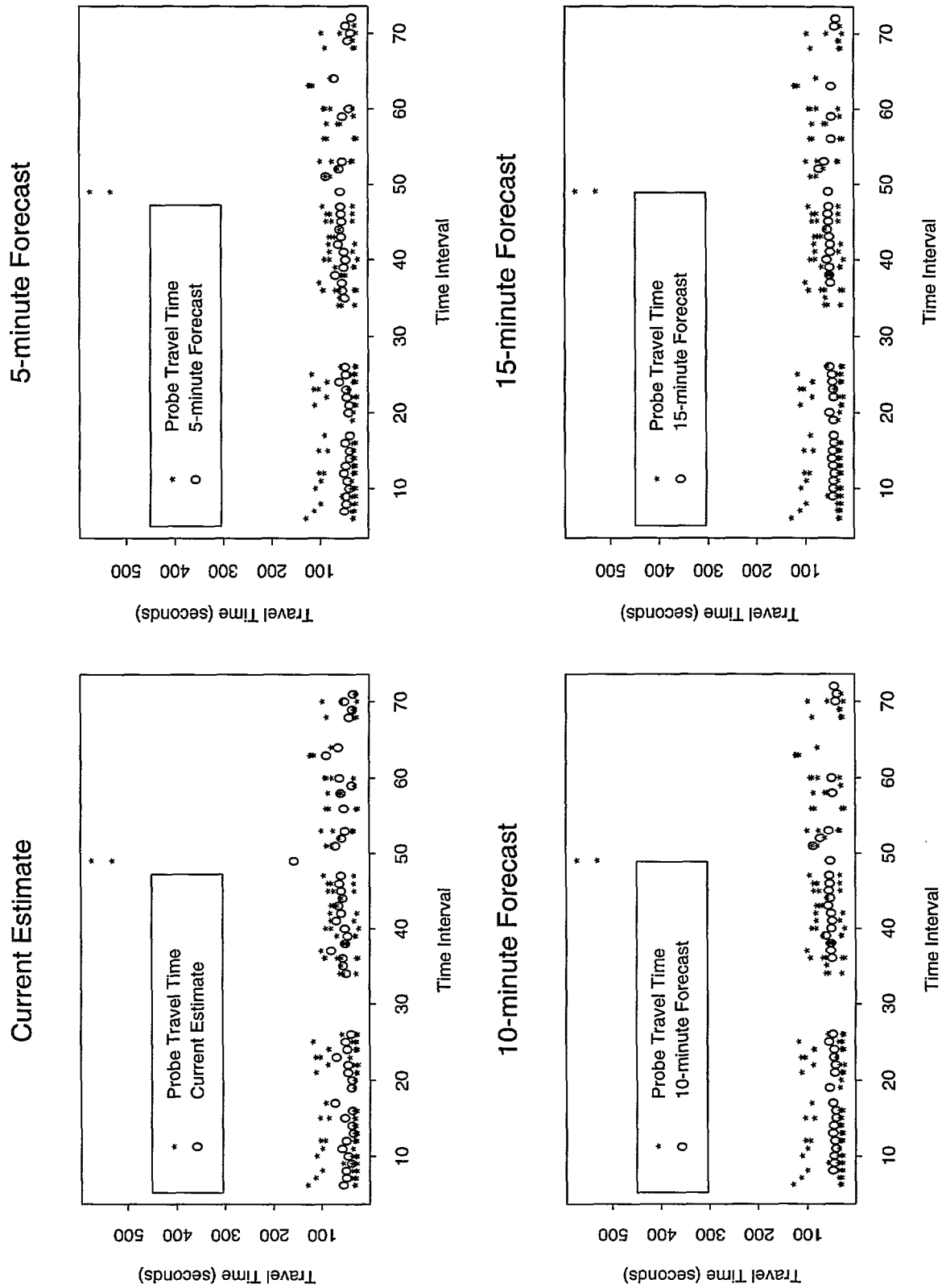
Figure 5: Individual Probe Travel Times and Probe-Only Estimates by Time Interval: Link 2, July 20

5 Results of TTP Evaluation

5.1 Selection of Links for Evaluation

Four links were selected for close examination from among the thirteen links driven. Two of these links have detectors and two do not and since two are very congested during the peak and the other two are less congested, there is one example in each of four categories (based on level of congestion and the presence of a volume/occupancy detector). Each of these cases is discussed separately. These four links can be characterized as:

- Link 2: no detector, less congested,

- Link 9: no detector, congested,

- Link 11: detector, less congested and

- Link 7: detector, congested.
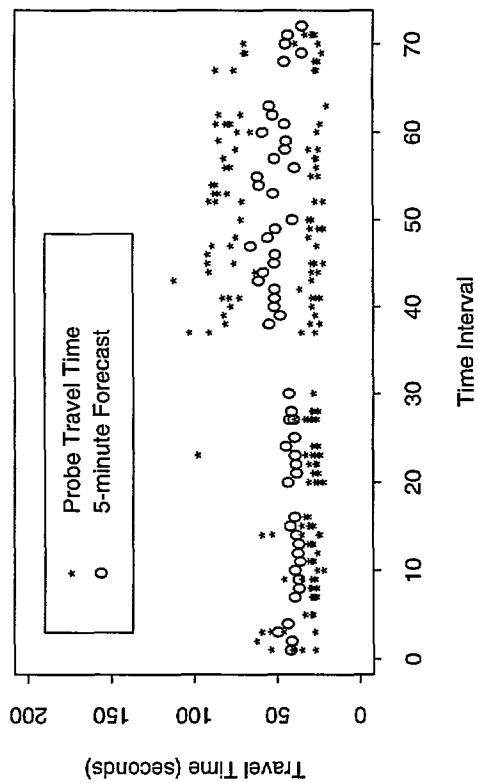
5.2 Probe Data Only

The evaluation of data collected by probes will be performed initially for the two links without detectors, Links 2 and 9. Later a comparison will be made on the other two links between travel-time estimates generated by detector and probe data and actual travel times.

5.2.1 Link 2: Less Congested

The evaluation in this section will use data from July 17, when the largest number of probe reports was collected. The basic data examined are displayed on Figure 6 which graphs the actual probe travel times and the predicted travel times. Notice that the scale of the y-axis is very different from Figure 5 and that there are actually eleven reports over one hundred seconds on Figure 5 and only two on Figure 6. On Figure 6 we can clearly see the effects of signal timing on traffic flow and its effect on the TTP algorithm.

Probe-recorded travel times are clustered in two ranges. Travel times in the lower range, from 20 - 40 seconds, were recorded by vehicles that received a green signal at the end of Link 2 (the intersection with Wheeling/McHenry, see Figure 3); vehicles that received a red signal had to wait to complete Link 2 and therefore recorded higher travel times, of 60 or more seconds. This is most evident in the peak period, from 4:00 pm to 6:00 pm (Intervals 36 to 60).
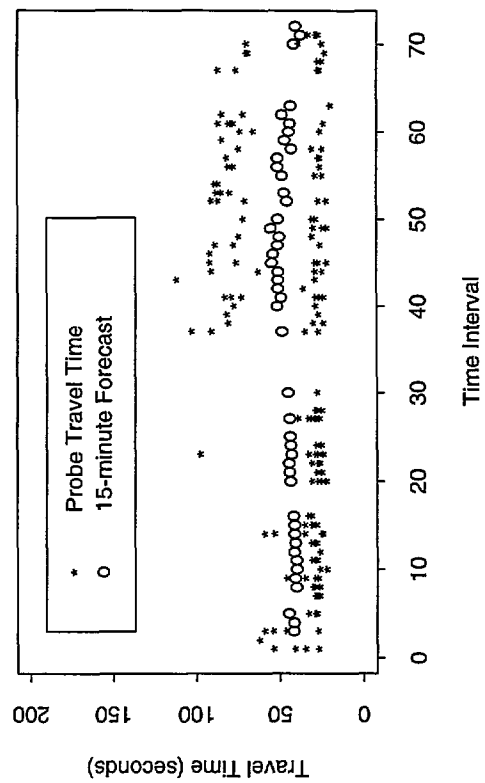
Figure 6: Individual Probe Travel Times and Probe-Only Estimates by Time Interval: Link 2, July 18

The upper left corner graph of Figure 6 shows the current estimates of travel time and the probe-reported travel times. During the first several hours the majority of the probes completed this link 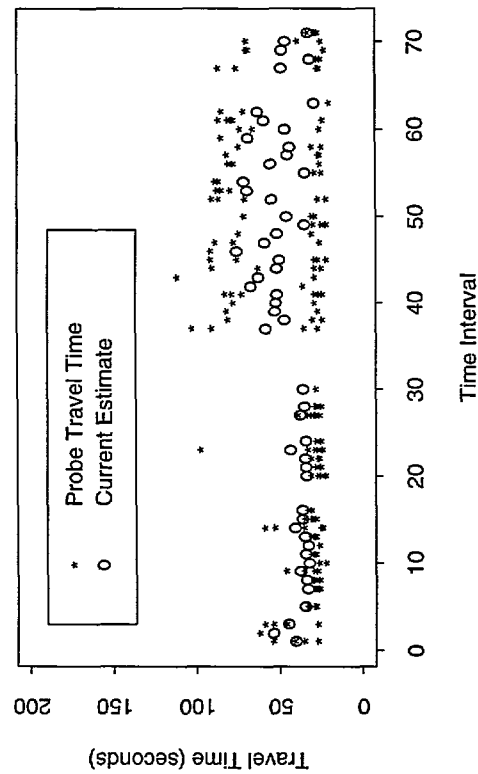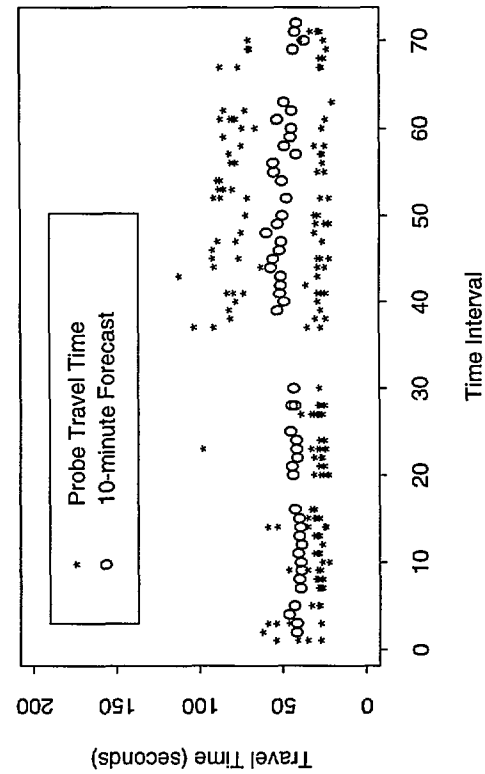in less than forty seconds. The prediction is higher than the majority of the readings; this is attributable to the higher travel times by probes that were probably queued at a red light. During the latter part of the day, mainly in the peak period, the estimate is a compromise between the two sets of probes, those that did and those that did not have to stop for a red light.

For the subsequent three graphs on Figure 6 the probe-reported travel times remain the same but the forecasts change. Two trends can be seen in the behavior of the TTP algorithm. First, the dispersion in the forecast values decreases with each subsequent forecast. Second, the maximum values of the forecasts decline; the minimum increases also but more moderately. In this way, the range of forecast travel times is smaller.

For the five-minute forecast there are several values near 35 seconds but nearly all of the fifteen-minute forecasts are over 40 seconds. At the high end the forecasts drop from 65 seconds for the five-minute forecast to 55 seconds for the fifteen-minute forecast. Current estimates as high as 75 seconds demonstrate how the travel-time estimates decrease from the current estimate to the fifteen-minute forecast.

This data is presented in an alternative format in Figure 7. The probe travel time (y-axis) is plotted against the current estimate and five, ten and fifteen-minute forecasts (x-axis). This figure also includes a line (a: = y) marking equality between probe travel time and the estimate. It is evident from Figure 7 that most of the actual probe-reported travel times are either well above or well below the estimated travel times. This again shows the effect of signals on travel times on relatively short links.

Figure 6 displays each probe report but since the TTP is one estimate for each five-minute period, we also show the mean probe travel time graphed with the TTP forecasts (Figure 8). The two figures, for the individual and mean probe data, are rather similar. While Figure 8 is a more true one-to-one comparison (of a 5-minute estimate against a 5-minute mean) we will continue to emphasize the figures which show the probe reports individually. These figures show how well the individual probe reports match the TTP forecasts, and the problems associated with using one value (the mean) to represent actual travel times with high variances.
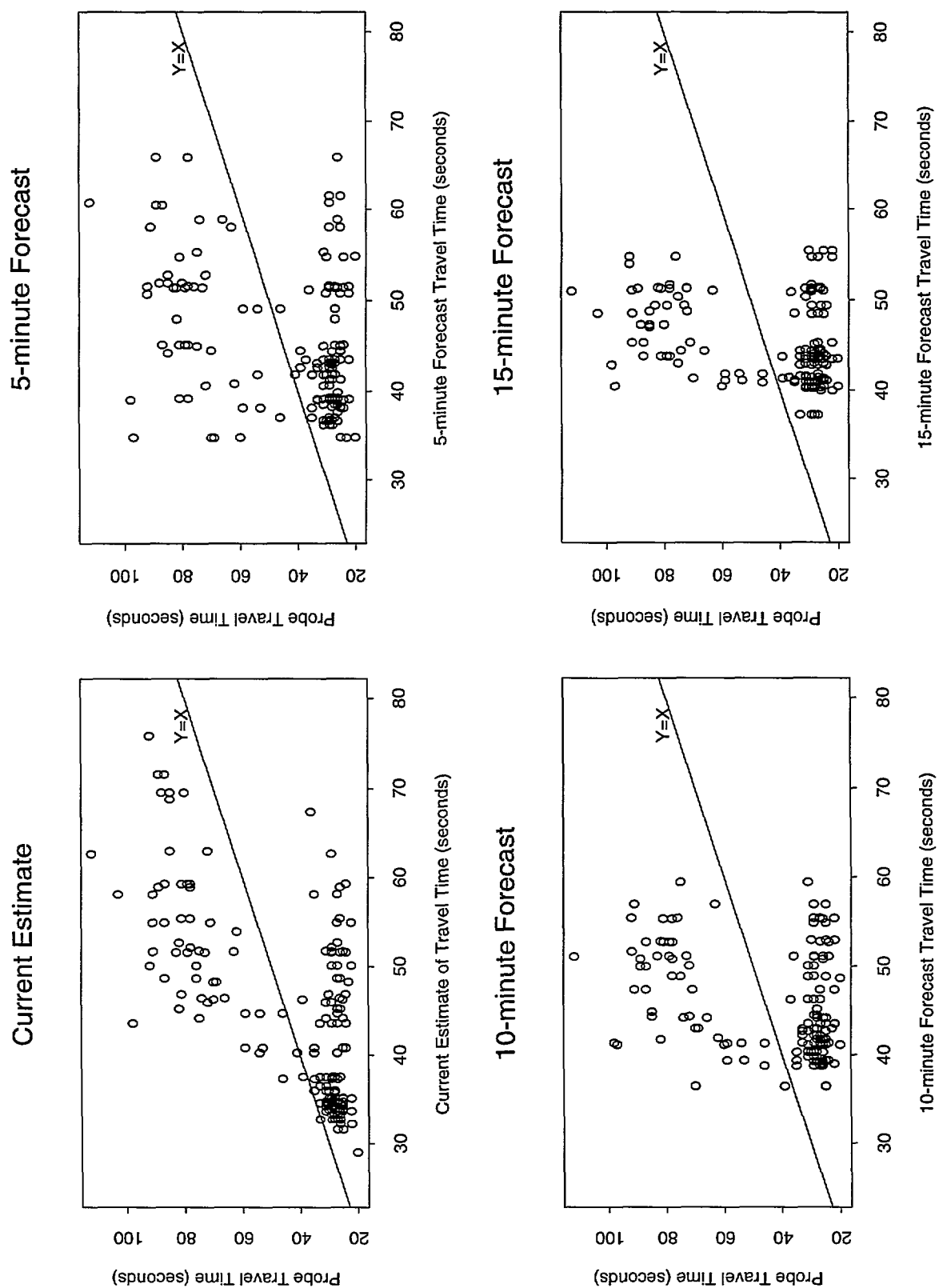
Figure 7: Probe Travel Times Plotted against Estimated and Forecast Travel Times: Link 2, July 17
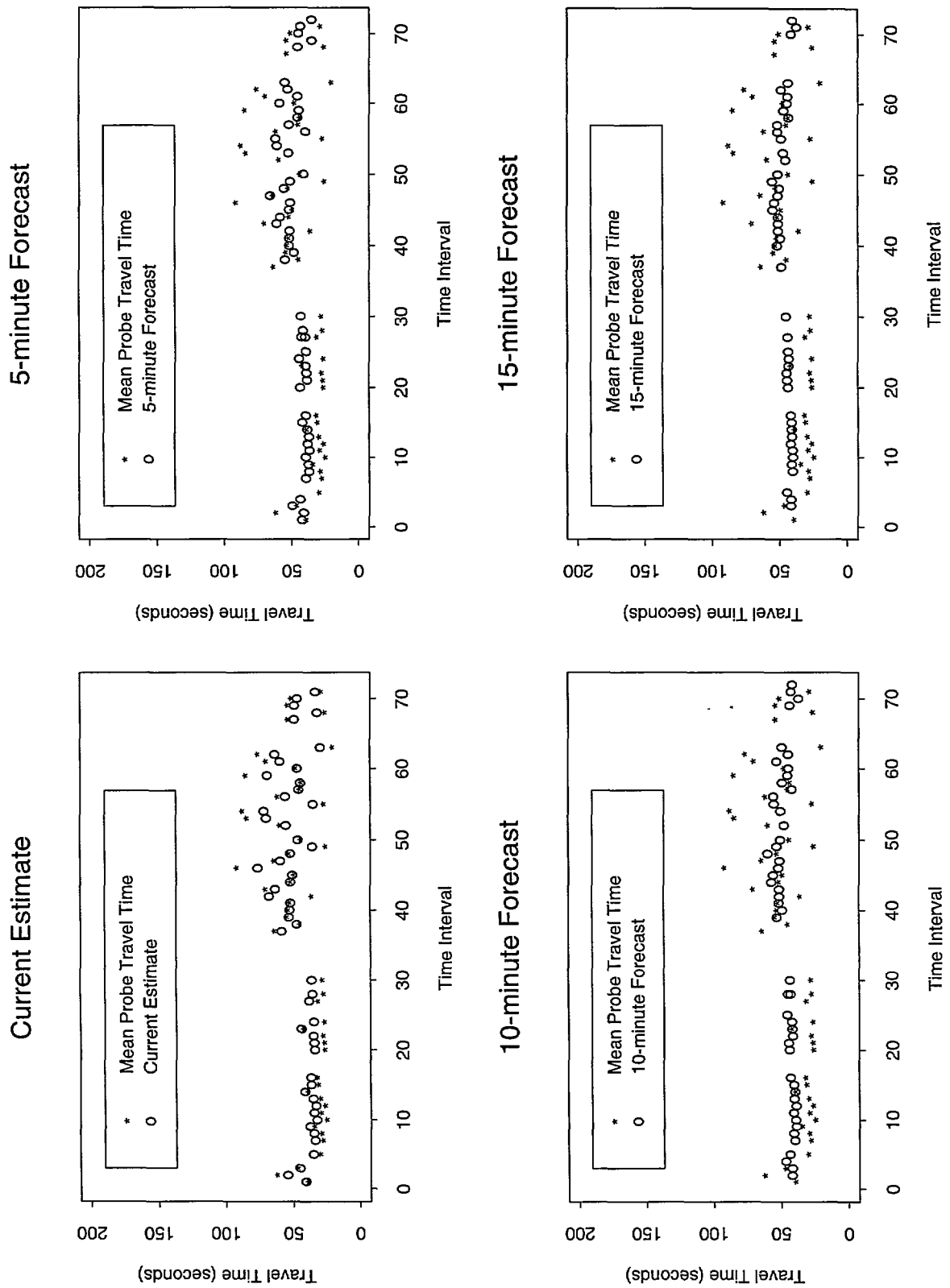
17

Figure 8: Five-Minute Mean Probe Travel Times and Probe-Only Estimates by Time Interval: Link 2, July 17

18

5.2.2 Link 9: Congested

Link 9 is a relatively long link (856 meters) which experiences a substantial increase in peak-period traffic. During the off-peak period the link is typically traversed in 50 - 100 seconds (Figure 9), but ten probe reports during the peak period were in excess of 300 seconds.

While the current travel-time estimates accurately reflect the probe reports, again the conservatism built into the algorithm is evident in the subsequent forecasts (five-minute to fifteen-minute forecasts). Even the current estimates do not reach the levels of the highest probe reports. At approximately 6:00 pm (Interval Number 60) there were four probe reports near the 500-second range but the estimates only reached 300 seconds.

During this same time-of-day interval the five-minute forecasts dropped to just over 200 seconds from 300 seconds for the current estimate. The forecasts continue to drop until they are all less than two hundred seconds for the fifteen-minute forecasts. In this latter case the TTPs illustrate a relatively symmetric pattern increasing to the peak (at approximately 5:00 pm, Interval Number 48) and declining thereafter. The patterns for the five-minute and ten-minute forecasts are much more irregular.

Again we examine the closeness of the match between probe and forecast travel times by graphing one against the other (Figure 10). In this case the y-axis extends to 500 seconds, compared with 120 seconds in Figure 7. Because of the many signal-cycle failures experienced in this link the distribution of probe travel times is not bimodal in character. The current estimates match the probe travel times reasonably well. Above 200 seconds, however, the probe times all exceed the estimates.

We show one more figure illustrating the comparison between the mean probe travel times and the travel-time forecasts for Link 9 (Figure 11). Even without this graph one can visualize the general relationship that the error in the estimate is small when the probe mean is small and it increases with the mean value. This is especially evident on the fifteen-minute graph.
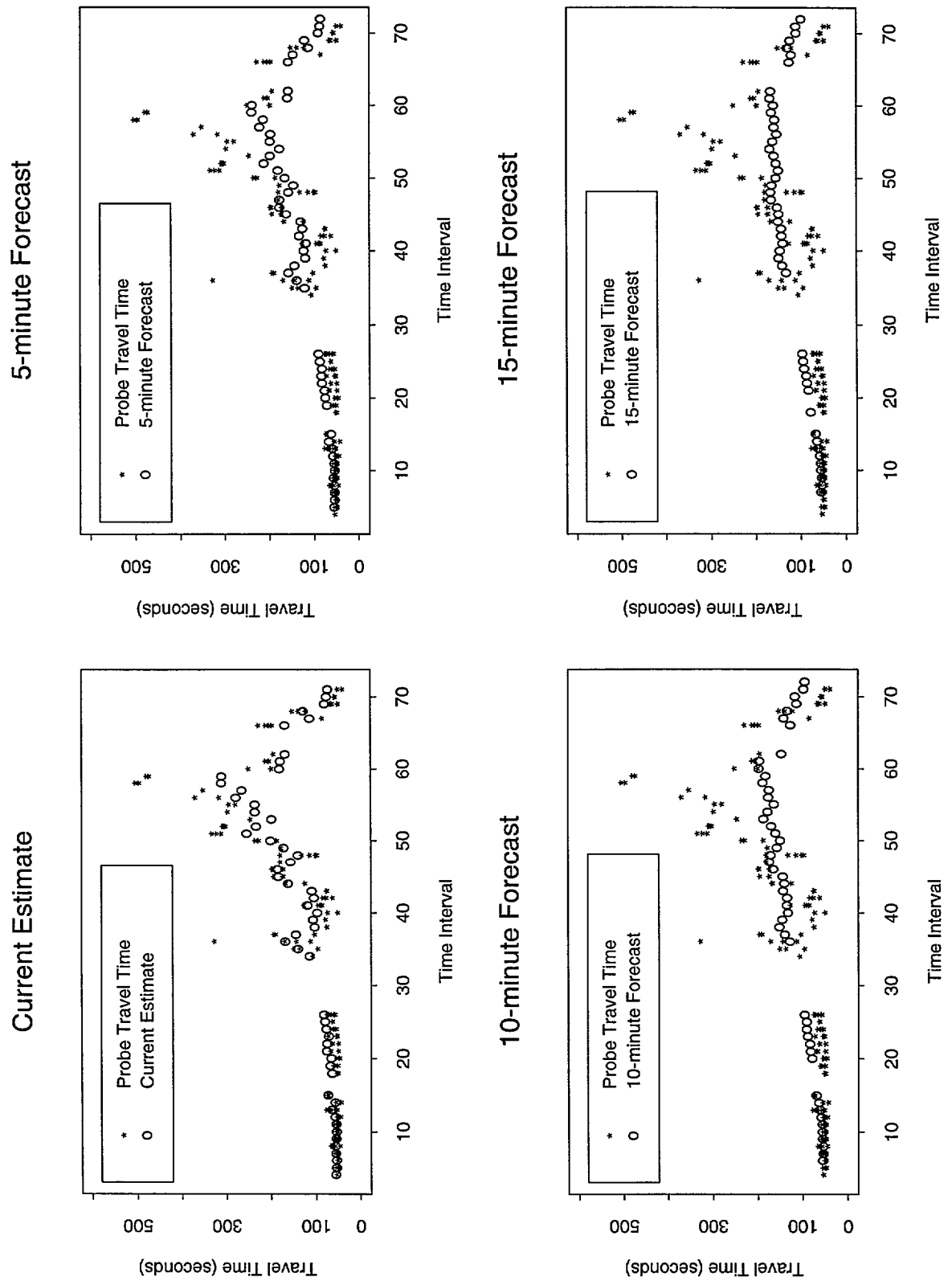
Figure 9: Individual Probe Travel Times and Probe-Only Estimates by Time Interval: Link 9, July 19
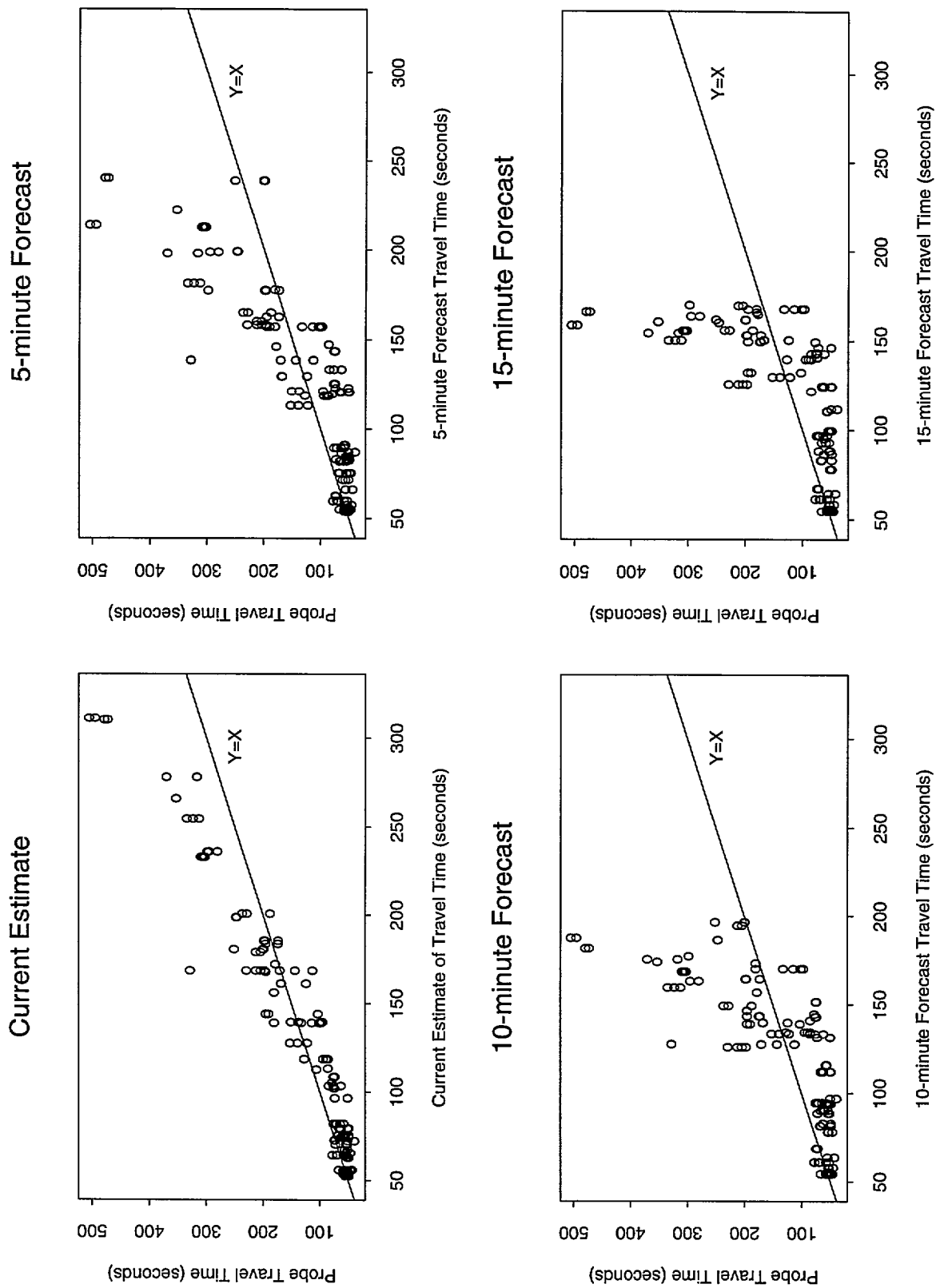
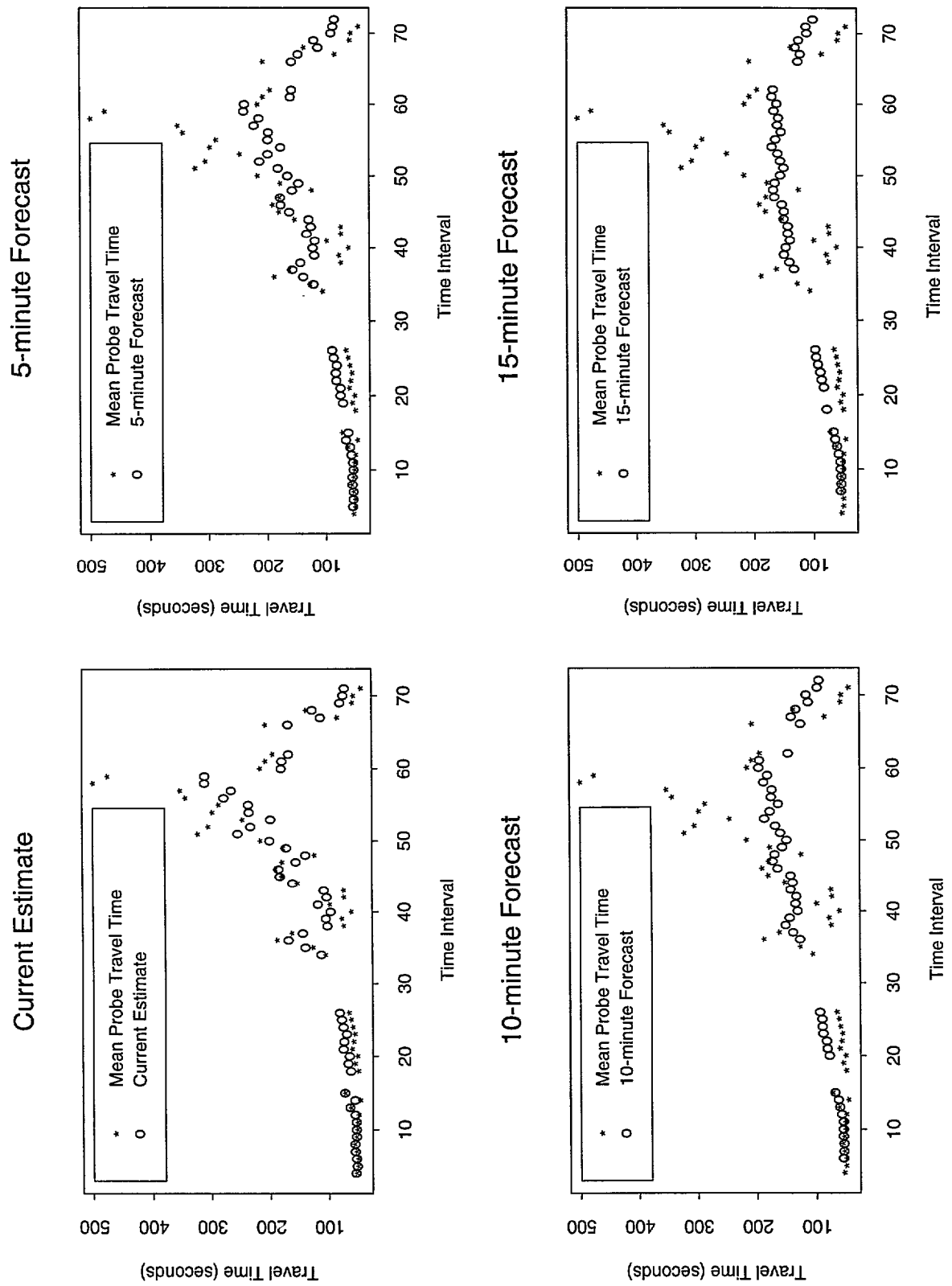Figure 10: Probe Travel Times Plotted against Estimated and Forecast Travel Times: Link 9, July 19

Figure 11: Five-Minute Mean Probe Travel Times and Probe-Only Estimates by Time
Interval: Link 9, July 19

5.3 Detector Data Only

Volume and occupancy detectors are available on two of the study links, Links 7 and 11, which are discussed in this section. These detector-based estimates are compared with probe reported travel times and with estimates based on probe data only.

5.3.1 Link 11: Less Congested

Link 11 is a relatively short link (457 meters) on Dundee Road with a large discount retailer and an automobile dealer on the north side and a series of small stores on the south side. It is downstream from Link 9 which experiences substantial congestion but there are several reasons why Link 11 has relatively little congestion. First, much of the Link 9 congestion has turned off Dundee Road onto McHenry and Wheeling Roads. Second, there is a separate turning lane at the end of Link 11 relieving some of the traffic buildup. Third, the link is shorter than the queue on Link 9 during the maximum peak and therefore cannot have the excessive delays found on Link 9.

Figure 12 displays the travel times of probes on Link 11 (*), the detector-only estimates marked with a + sign and the estimates based only on probe data marked by the symbol o. For the current estimate as well as the three subsequent forecasts the detector-based estimates represent a reasonable approximation of the actual probe activity. On the plot of fifteen-minute forecast travel times it appears that the forecast travel times (40 to 60 seconds) are a good compromise between the travel times of those probe vehicles that had to stop at a red light (over 60 seconds) and those that did not (travel times of less than 40 seconds). Also there is little difference between the detector-only and the probe-only forecasts. The greatest differences occur for the current estimate but for each subsequent forecast the differences diminish.

5.3.2 Link 7: Congested

Link 7 is a southbound link with a right turn at the end of the link. At all times there is more traffic here than on Link 11, the other detectorized link. During the peak period there are major delays at this intersection in nearly all directions. As a consequence the detectors become saturated during most of the data-collection period and they provided relatively little useful information.

For the current estimates, the detector estimates (Figure 13) are around 60 seconds during the time intervals before the beginning of the peak period while most of the probes completed the link in over 100 seconds at this time. During the peak period the detector estimates are less useful. For a fuller discussion of this, see Berka et al. (1996).

The probe estimates and forecasts perform considerably better but due to their conservative nature they understate congested traffic conditions. This suggests the need for an adjustment in the algorithm, an important lesson learned in this evaluation process.
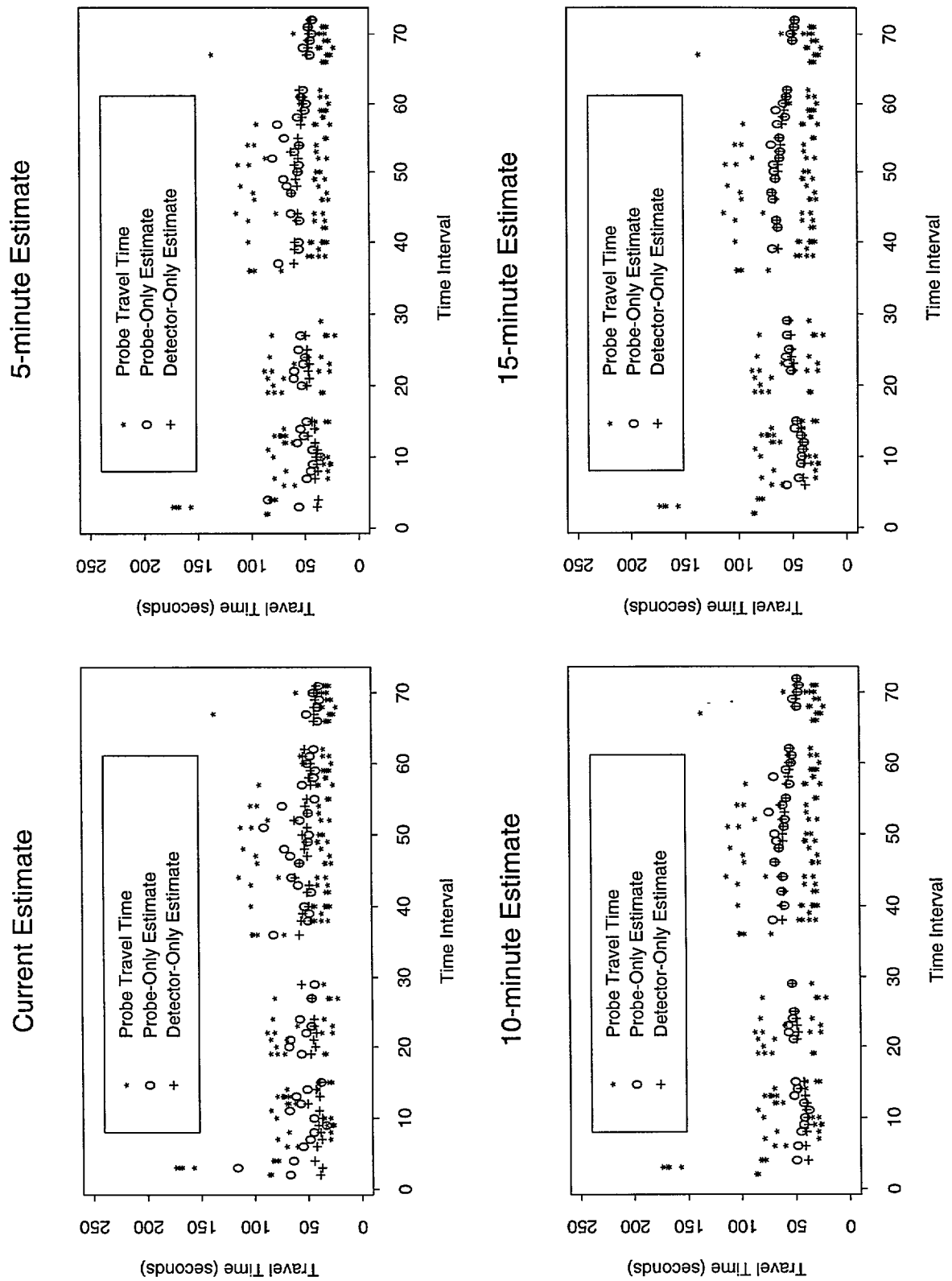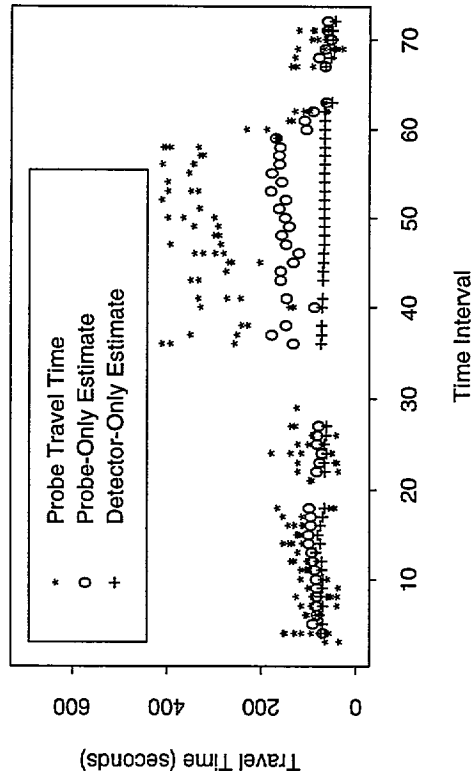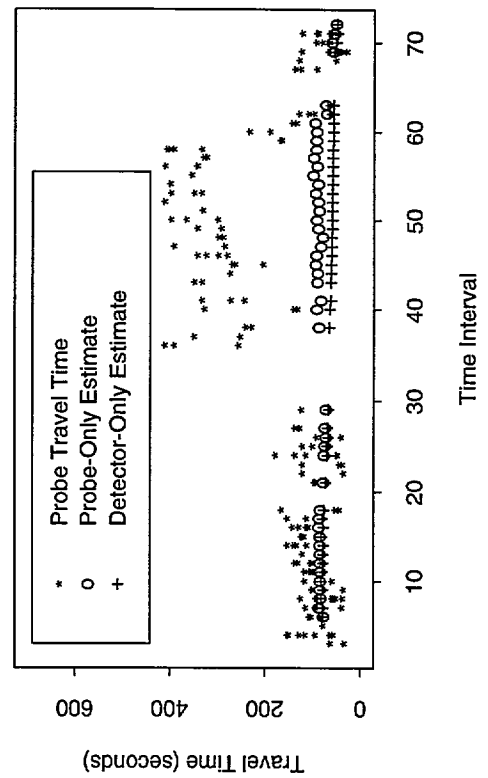
Figure 12: Individual Probe Travel Times and Detector-Only and Probe-Only Estimates: Link 11, July 17
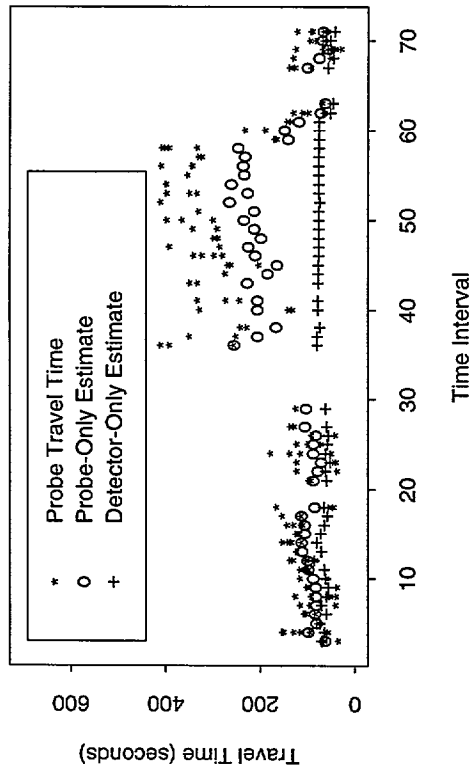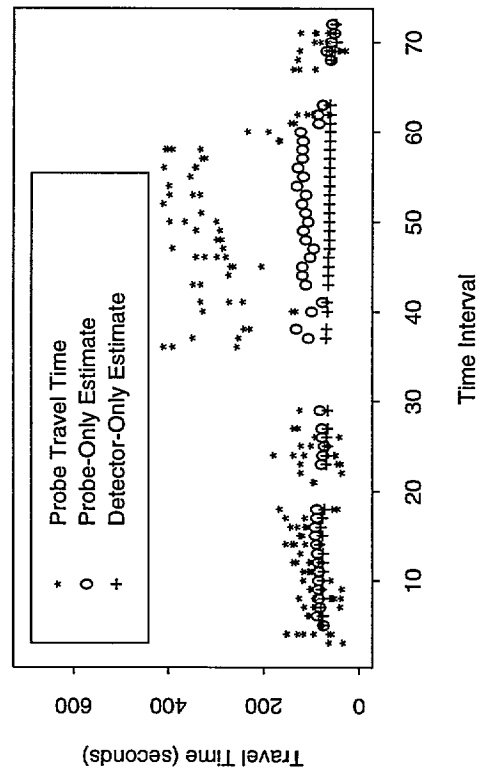
Figure 13: Individual Probe Travel Times and Detector-Only and Probe-Only Estimates: Link 7, July 18

5.4   Fused Probe and Detector Data

In this section we use fused data by combining reports from both probes and detectors. As a consequence several of the figures will resemble those seen previously. Again the analysis uses Links 7 and 11, the detectorized links.

5.4.1 Link 11: Less Congested

In the previous section is was evident that Link 11 had relatively little congestion and that both detector data and probe data yielded good estimates of travel time. Figure 14 shows actual probe travel times and the estimates based on fused data. As anticipated this figure is very similar to Figure 12, which shows the detector and probe estimates separately.

5.4.2 Link 7: Congested

Since the probe-only and the detector-only estimates varied substantially on Link 7, it is particularly interesting. Figure 15 displays the estimates based on fused data which look very much like a compromise between the probe-only and detector-only estimates (Figure 13). In the current estimates this compromise pulls the already conservative probe-only estimates downward and they are therefore even less representative of the actual travel times experienced. It is clear that from comparing Figures 13 and 15 that probe-only estimates are in this case superior to the fused-data estimates.

With the probe and detector data inputs used in this study to estimate TTPs, it is apparent that on congested links only probe data should be used and not fused (probe and detector) data. This fusion should only be performed during uncongested periods, but these periods are of minimal interest. They do not result in active transmission to the MNA; during uncongested periods the static profiles are adequate.

Figure 14: Individual Probe Travel Times and Estimates based on Fused Probe and Detector Data: Link 11, July 17
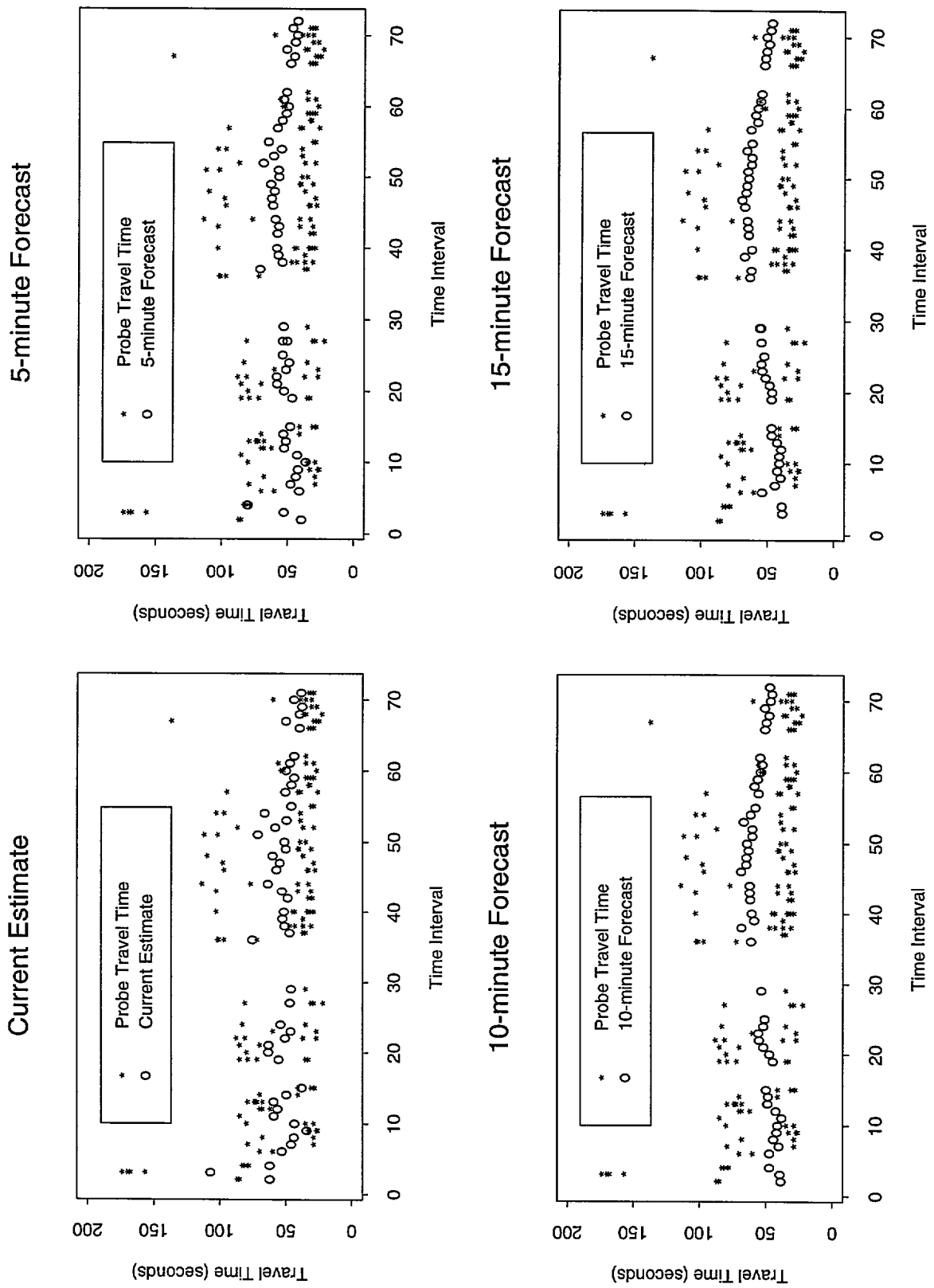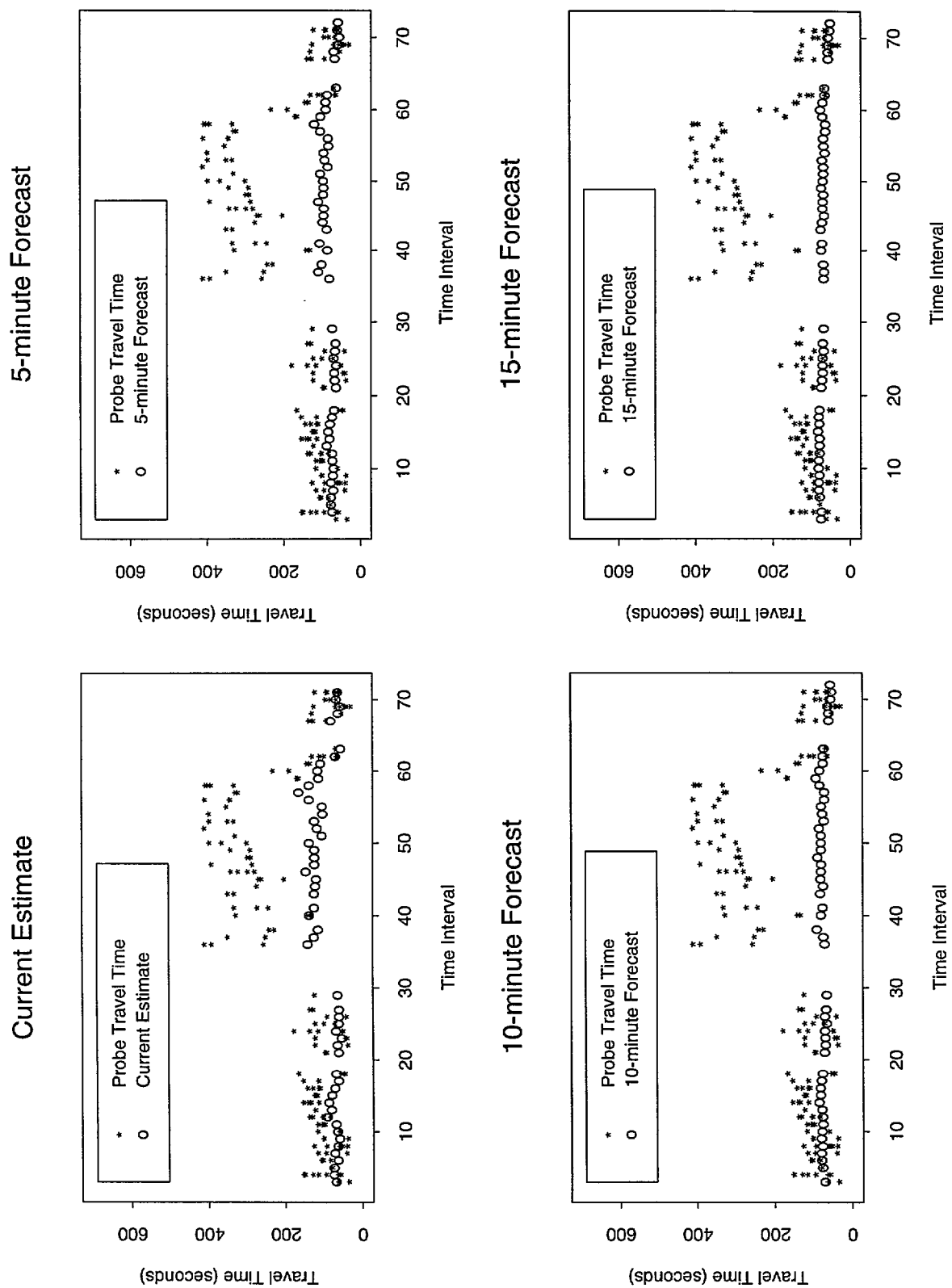
Figure 15: Individual Probe Travel Times and Estimates based on Fused Probe and Detector Data: Link 7, July 18

5.5　Probe Data Only at Varying Deployment Levels

In this section we will consider the current estimates and the five, ten and fifteen-minute forecasts of travel time with varying amounts of probe data input to the TTP algorithm. It is evident that a useful evaluation will consist of using only probe data in this section and not fusing these data with detector data. We originally intended to fuse probe data with detector data but in light of the findings in previous sections this seems unwise.

Starting with the current estimate only five-minute intervals with *at least four* probe reports are considered. We initially considered up to five probe reports per five-minute period but there were so few such periods that we substantially increased the sample by decreasing the number of probe reports to four. Those five-minute intervals with more than four reports have the excess probe reports eliminated in a random process. The estimate is made using the remaining four probe reports. In the next step one of the four probe reports is randomly deleted and all other five-minute intervals with exactly three probe reports are added. In this manner each subsequent step has a greater number of five-minute intervals with which to make a comparison between estimated and actual travel times.

We selected Link 7 for this analysis. It has the greatest congestion of any of the study links and even during the off-peak period is characterized by heavy traffic. The congested periods are far more interesting; during free-flow conditions we have already seen that both detectors and probes perform very well. Moreover, during these low-congestion periods very few updates would be sent to the MNA.

5.5.1 Current Travel-Time Estimates

We observed earlier that the current estimate was generally the most accurate of the four estimates (one "estimate" and three "forecasts"). We therefore start with these current estimates and examine them with initially one probe report per five-minute interval, then with two probes, then three and finally four probes per five-minute interval.

Figure 16 illustrates the current estimates using one to four probe reports and the actual probe travel times for the 72 five-minute intervals from 1:00 pm to 7:00 pm on July 18, 1995. It is obvious that the estimates, the o symbol, decrease in number as the number of probe reports per five-minute interval increases. While there are 59 five-minute intervals with at least one probe report there are only 51 with two probe reports, 29 with three and 17 with four (there are also 9 with at least five probe reports but this is too sparse to be included in this analysis).

Since we operated with a fixed number of vehicles throughout the day the frequency of multiple probe reports decreases as the study route travel time increases. This is logical but it results in very few five-minute intervals with at least four probe reports during the peak period. There are **24** five-minute periods during the **4:00** to 6:00 pm

peak period but only 9 with three reports and only 3 with four probe reports. By contrast there were 9 five-minute intervals during the two-hour period from 1:00 pm to 3:00 pm with four probe reports. As a consequence the amount of available data decreases as the problem becomes interesting.

During the first part of the day the estimates hover around one hundred seconds and do not deviate by more than +/- fifty seconds. The one-probe estimate dips down to approximately 50 seconds but the minimums are higher for the subsequent forecasts. Before the peak period there are several one-probe estimates near fifty seconds, only one for the two-probe estimate and the lowest three-probe estimate is even over sixty seconds. The high values before the peak period decline as the number of probes in the estimate increases but not as noticeably.

During the peak period the one-probe estimates range from under 150 seconds to just over 250 seconds. This is generally true for the two-probe estimate but the low values for the three-probe estimates drop out; all estimates are in excess of 200 seconds.

5.5.2 Five-Minute Forecasts

The same general pattern continues for the five-minute forecast. The forecasts for the early part of the day (Figure 17) fall into a slightly smaller range than exhibited for the current estimate. The most substantial changes are during the peak period when the forecasts drop by at least 50 seconds. Comparing the peak periods for the current estimate and the five-minute forecast (Figures 16 and 17) the estimates drop from approximately 250 seconds to 200 seconds.

Within Figure 17 there is relatively little difference. From time interval zero (1:00 pm) to interval number 60 (6:00 pm) the forecasts tend to move upward from approximately sixty seconds to 150 seconds. The major difference is that the number of estimates decreases as the number of probe reports increases from one to four.

5.5.3 Ten-Minute Forecasts

Figure 18 shows that the dispersion in the forecasts has declined (the vertical and horizontal axes are identical for Figures 16 through 19).

Visual inspection shows relatively little difference in the estimates from one probe to four probes per five-minute data-input interval. A subsequent section will examine actual values.

5.5.4 Fifteen-Minute Forecasts

For the last forecast we see the same pattern we have witnessed throughout this report, the forecasts become increasingly more conservative into the future. This is evident regardless how many probes are used (Figure 19). Because the dispersion in the estimates has declined, in this last set of estimates the change from one to four probes is very slight.

Figure 16: Individual Probe Travel Times and Current Estimates with Varying Numbers of Probe Reports: Link 7, July 18

Figure 17: Individual Probe Travel Times and Five-Minute Forecasts with Varying Numbers of Probe Reports: Link 7, July 18
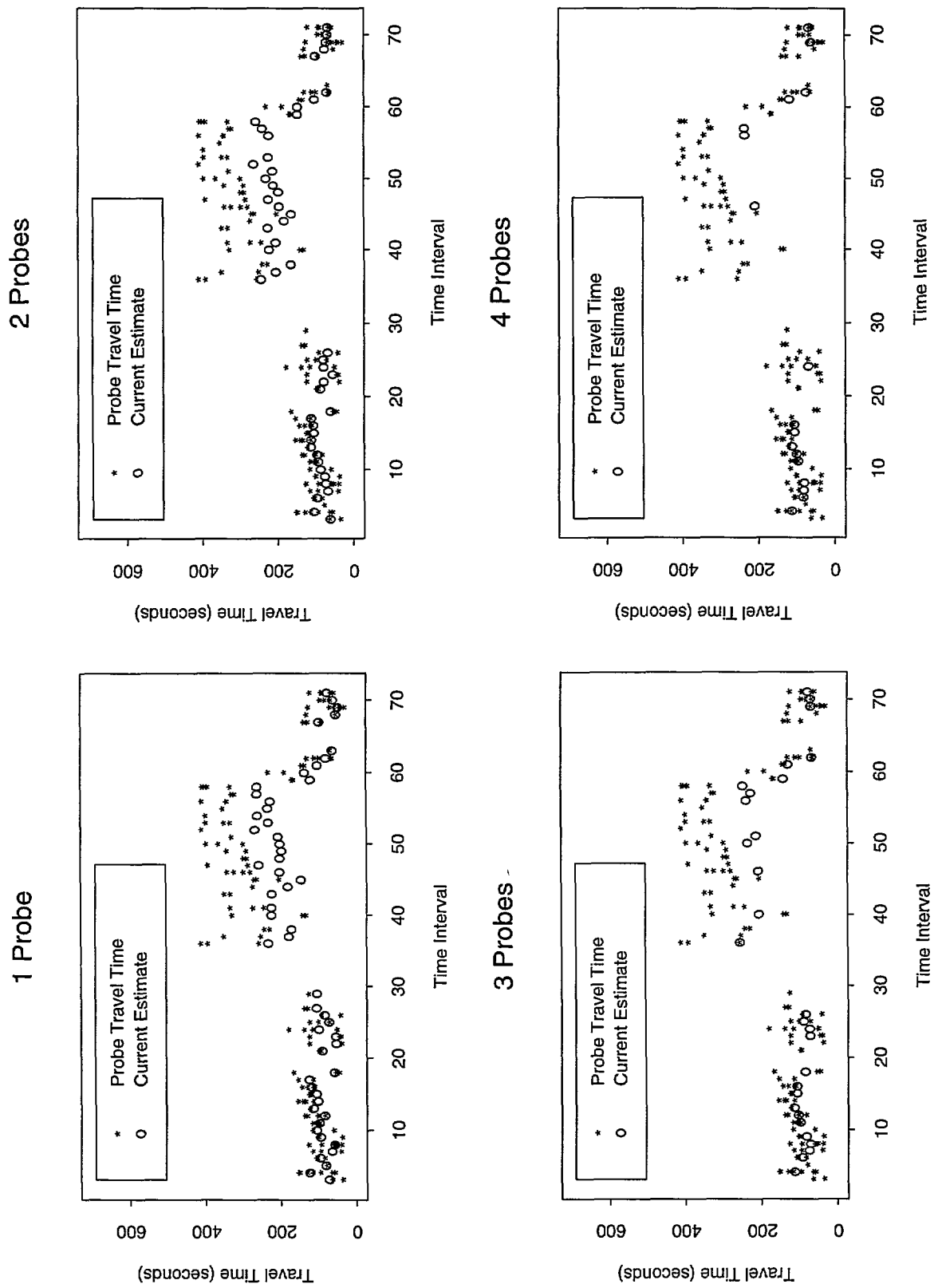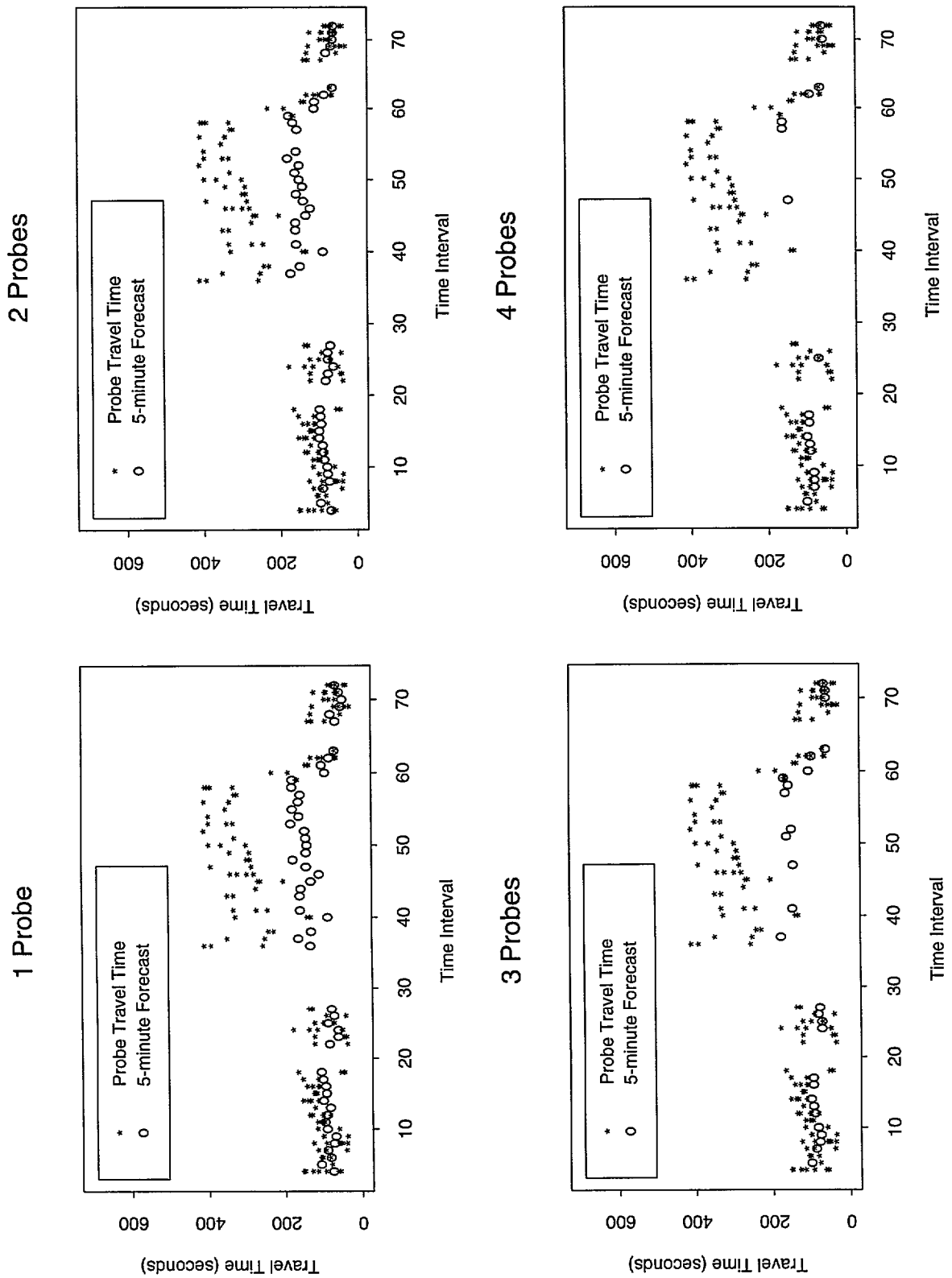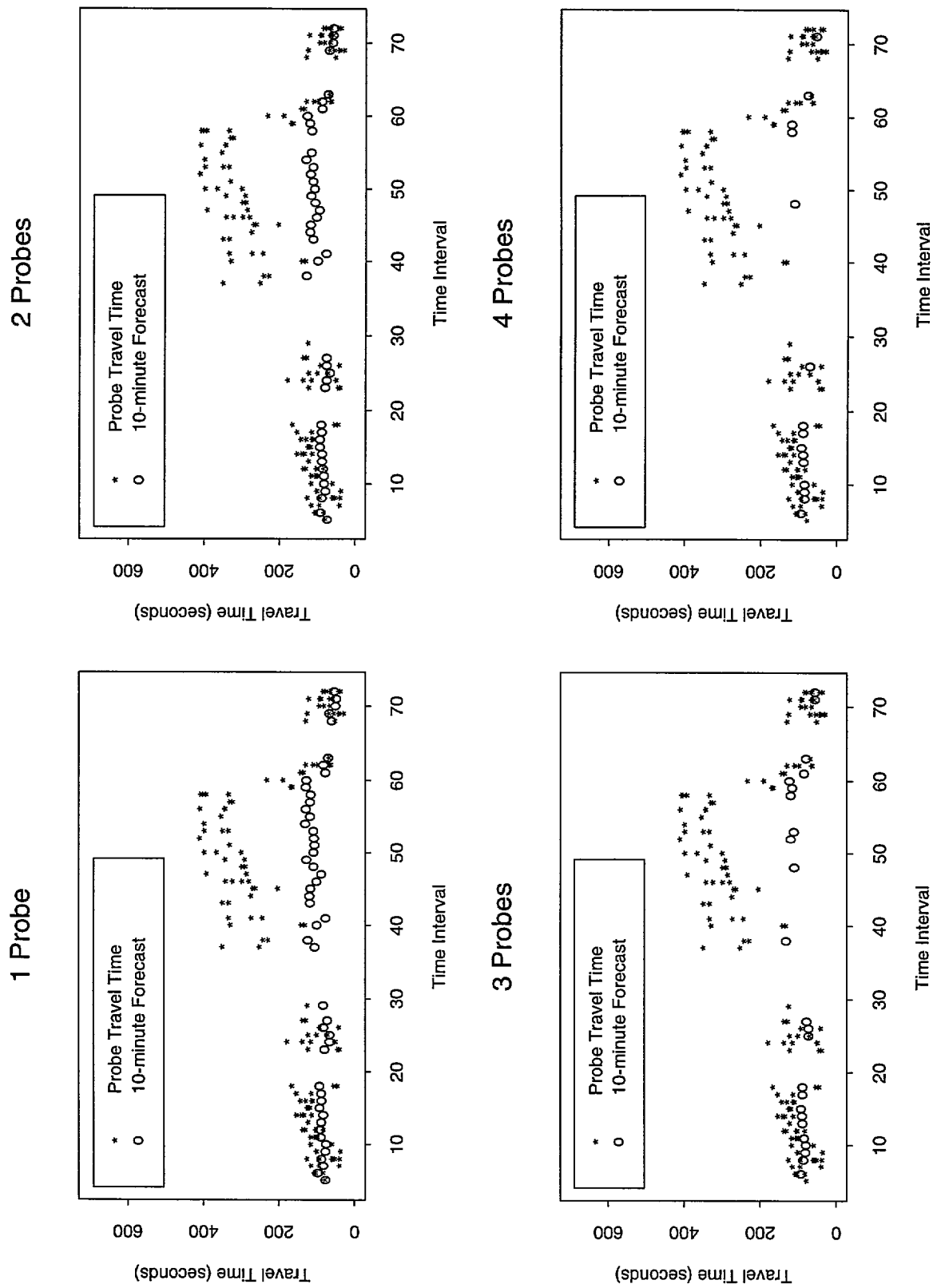
Figure 18: Individual Probe Travel Times and Ten-Minute Forecasts with Varying Numbers of Probe Reports: Link 7, July 18
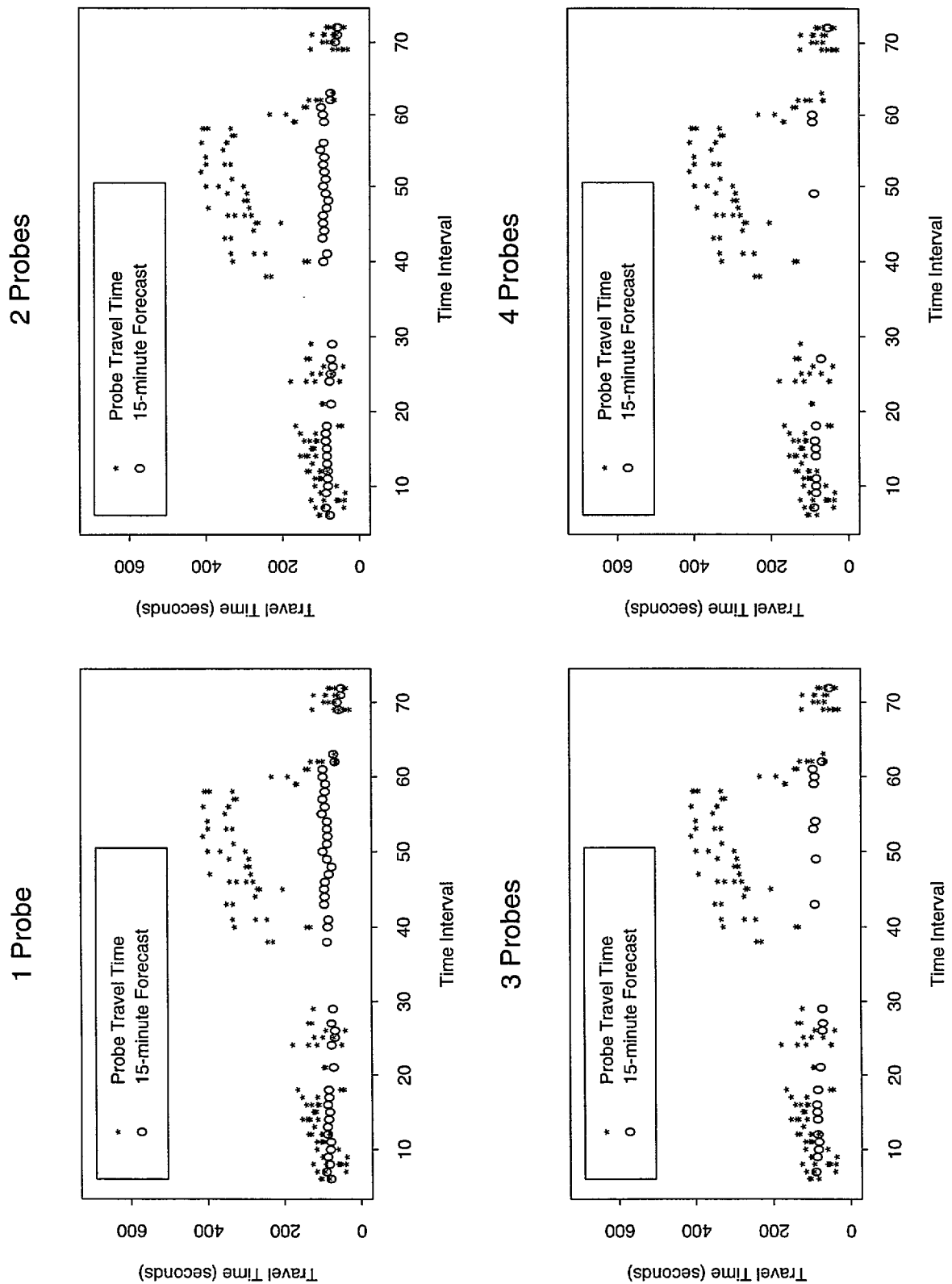
Figure 19: Individual Probe Travel Times and Fifteen-Minute Forecasts with Varying Numbers of Probe Reports: Link 7, July 18

5.5.5 Overview of Varying Number of Probe Reports

Another way to evaluate the performance of the TTP algorithm is to examine a table (Table 3) of the seventeen five-minute periods between 1:00 pm and 7:00 pm on July 18 with at least four probe-reported travel times on Link 7. This table reconfirms the earlier finding that the TTP algorithm is rather conservative and that the greatest change in travel-time estimates is for the current period as probe reports are added. By focusing on this column it is clear that in only a few cases there is a substantial change in the estimate after three probe reports have been included.

The first five-minute period (at 1:23:09 pm) started with a current estimate of 123 seconds which dropped to 106 seconds after the second probe report. The third probe report brought it up to 112 seconds and it did not change more than two seconds with the fourth and fifth probe reports. The greatest changes in the current estimate from three to four probes occurred at 1:33:01, 1:43:02, 5:48:25 and 6:08:14 but in all four cases the change was just under 10 seconds. For most of the other 5-minute periods the changes in estimates were only a few seconds.

The same pattern of small changes is more evident for the three forecasts. There are only minor changes after three probe reports have been included. Even during the peak period, when the driving times are high there is little change after the third probe report. All of the estimates between 4:00 pm and 6:00 pm are over three and a half minutes but the largest change in the forecasts is less than ten seconds. There are some periods where the estimates remain largely unchanged. This is true for the 2:08:01 pm and 2:18:00 pm periods.

The 15-minute estimates are the most conservative and therefore need the fewest probe reports. After three probe reports there are very few examples in which the changes are in excess of two seconds with the inclusion of an additional probe report, either from three to four or from four to five probe reports. If the algorithm were changed then it would likely be more sensitive to the number of probe reports but the present version seems to need no more than three probe reports.

Note that in reading across the table (from current estimate to 5, 10 and 15-minute forecasts), the forecast travel times decrease in all five-minute periods except for those beginning at 1:33:01 pm, 1:38:00 pm and 1:43:02 pm. During these time periods probe vehicles reported low travel times and the forecasts were higher to reflect more typical conditions.

Table 3: Travel-Time Estimates for 5-minute Periods with 4 or more Probe Reports: Link 7, July 18

Time	Current	5-min	l0-min	15-min	# Probes
1: 23:09	123.43	106.62	96.88	91.37	1
1: 23:09	106.03	96.18	90.61	87.61	2
1: 23:09	112.03	99.78	92.77	88.91	3
1: 23:09	114.43	101.22	93.64	89.43	4
1: 23:09	113.23	100.50	93.20	89.17	5
1: 33:0l	94.71	90.07	87.63	86.50	1
1: 33:0l	95.91	90.79	88.06	86.76	2
1: 33:0l	91.11	87.91	86.33	85.73	3
1: 33:0l	82.86	82.96	83.36	83.94	4
1: 38:00	64.45	72.25	77.28	80.63	1
1: 38:00	66.85	73.69	78.14	81.15	2
1: 38:00	74.65	78.37	80.95	82.84	3
1: 38:00	81.55	82.51	83.43	84.33	4
1: 43:02	56.99	68.12	75.14	79.02	1
1: 43:02	73.19	77.84	80.97	82.52.	2
1: 43:02	70.79	76.40	80.10	82.00	3
1: 43:02	80.69	82.34	83.67	84.14	4
1: 58:07	96.94	91.19	87.42	84.83	1
1: 58:07	94.54	89.75	86.56	84.31	2
1: 58:07	97.54	91.55	87.64	84.96	3
1: 58:07	97.09	91.28	87.48	84.86	4
2: 03:05	82.83	82.40	81.82	81.16	1
2: 03:05	97.23	91.04	87.00	84.27	2
2: 03:05	103.23	94.64	89.16	85.56	3
2: 03:05	100.83	93.20	88.30	85.04	4
2: 03:05	99.87	92.63	87.96	84.84	5
2: 08:0l	113.11	100.24	92.21	87.06	1
2: 08:0l	113.11	100.24	92.21	87.06	2
2: 08:0l	114.31	100.96	92.64	87.32	3
2: 08:0l	112.51	99.88	91.99	86.93	4
2: 08:0l	111.43	99.23	91.60	86.70	5
2: 18:00	104.66	94.53	88.14	83.97	1
2: 18:00	104.66	94.53	88.14	83.97	2
2: 18:00	105.26	94.89	88.36	84.10	3
2: 18:00	104.96	94.71	88.25	84.04	4

Time	Current	5-min	l0-min	15-min	# Probes
2: 22:58	117.53	101.94	92.25	86.13	1
2: 22:58	107.33	95.82	88.58	83.93	2
2: 22:58	104.93	94.38	87.72	83.41	3
2: 22:58	106.28	95.19	88.20	83.70	4
3: 03:04	98.17	87.74	81.17	76.89	1
3: 03:04	78.97	76.22	74.26	72.75	2
3: 03:04	72.37	72.26	71.88	71.32	3
3: 03:04	68.77	70.10	70.58	70.54	4
3: 03:04	77.77	75.50	73.82	72.49	5
4: 53:0l	200.89	142.52	107.60	86.55	1
4: 53:0l	195.49	139.28	105.65	85.38	2
4: 53:0l	205.69	145.40	109.33	87.58	3
4: 53:0l	208.69	147.20	110.41	88.23	4
4: 53:0l	209.89	147.92	110.84	88.49	5
5: 43:17	227.09	157.44	115.55	90.32	1
5: 43:17	223.49	155.28	114.25	89.54	2
5: 43:17	237.89	163.92	119.44	92.65	3
5: 43:17	235.49	162.48	118.57	92.13	4
5: 48:25	262.39	178.52	128.10	97.74	1
5: 48:25	240.79	165.56	120.32	93.08	2
5: 48:25	226.39	156.92	115.14	89.97	3
5: 48:25	235.99	162.68	118.59	92.04	4
5: 48:25	231.91	160.23	117.12	91.16	5
6: 08:14	101.79	81.76	69.64	62.27	1
6: 08:14	104.19	83.20	70.50	62.79	2
6: 08:14	127.59	97.24	78.93	67.84	3
6: 08:14	117.69	91.30	75.36	65.70	4
6: 13:02	79.49	68.28	61.45	57.26	1
6: 13:02	69.29	62.16	57.78	55.05	2
6: 13:02	65.69	60.00	56.48	54.28	3
6: 13:02	73.49	64.68	59.29	55.96	4
6: 13:02	71.09	63.24	58.43	55.44	5
6: 48:33	45.79	47.36	48.20	48.61	1
6: 48:33	70.39	62.12	57.06	53.92	2
6: 48133	66.79	59.96	55.76	53.14	3
6: 48:33	61.39	56.72	53.82	51.98	4
6: 48:33	59.59	55.64	53.17	51.59	5
6: 58:37	74.99	64.68	58.39	54.52	1
6: 58:37	67.19	60.00	55.58	52.84	2
6: 58:37	75.59	65.04	58.61	54.65	3
6: 58:37	67.19	60.00	55.58	52.84	4
6: 58:37	64.79	58.56	54.72	52.32	

6 Conclusion

This study has compared actual probe travel times with travel-time predictions from the travel-time prediction algorithm. The comparisons were performed on four links on our study route. Two links with volume-capacity detectors were selected for detailed examination. TTP estimates and probe reports were also compared on two links which did not have detectors. In the detectorized and non-detectorized links chosen for study one link was highly congested during the peak periods and the other had far less congestion. This provided a mix of probe and detector data under varying traffic conditions which allowed a good overview of the TTP algorithm.

Both detector and probe data performed well during the off-peak period. During the peak period the detectors quickly became saturated and yielded unreliable travel-time predictions. This was especially true for Link 7 which was congested outside the predefined 4:00 to 6:00 pm peak period.

The probe-based predictions were more accurate but during the peak periods they also substantially underestimated actual travel times. This reflects the decision (to use a conservative travel-time prediction) made in the development of the algorithm but this evaluation suggests that it be adjusted to reflect these underestimations. In a subsequent deployment this adjustment can be made and the algorithm can produce more accurate predictions.

The present algorithm, however, performs exceptionally well when there is a small number of outliers during a five-minute time-of-day interval. These aberrations are largely ignored by the TTP as they should be. This was particularly evident in a case on Link 2 in which two probes in the same five-minute interval had travel times over five hundred seconds while all of the probes in the previous and subsequent intervals had travel times of one hundred seconds or less. The TTP forecasts did not pursue these isolated probe reports, demonstrating the value of the existing algorithm in treating this case.

Lastly, the effect of varying the number of probe reports during the five-minute intervals was examined. The probe data during these five-minute intervals represents the input to the TTP process and one would logically expect better results with more probe reports. While this is generally true we are more interested in the optimal number of probe reports. All intervals with at least four probe reports per interval were examined. Probe reports were then randomly deleted to determine the effects of decreasing the number of probe reports. This examination suggests that in most instances three probe reports are adequate to provide reasonable estimates. Increasing the number of probe reports to more than three caused very little change in the resultant travel-time forecasts. This finding is in concert with the findings of the frequency of probe reports study (see Sen, 1996) which indicated that the standard error of the mean travel times tends to stabilize after about three reports; the variance of travel times remains moderately high with additional probe reports and does not approach zero.

References

Berka S. Condie, H. and Sheffey A. (1996) *ADVANCE Evaluation: Detector Travel Time Conversion* and *Fusion* of Probe and Detector Data, Urban Transportation Center, University of Illinois, Chicago.

Berka S., Tian X. and Tarko A. (1995) *Data Fusion Algorithm for ADVANCE Release* 2.0, ADVANCE Working Papers Series, Number *48,* Urban Transportation Center, University of Illinois, Chicago.

Liu N. and Sen A. (1995) T*ravel* Time *Prediction Algorithm for ADVANCE, Release* 2.0, ADVANCE Working Papers Series, Number 47, Urban Transportation Center, University of Illinois, Chicago.

Mathes M. and Sen A. (1995) *Static Estimates of Travel Times* in *ADVANCE: Release 2.0 SPU Algorithm Report and Detail Design Document* (#8600), ADVANCE Working Papers Series, Number 49, Urban Transportation Center, University of Illinois, Chicago.

Sen A. (1996) *ADVANCE Evaluation: Frequency of Probe Reports, Urban Transporta*tion Center, University of Illinois, Chicago.

Sen A., Condie H., Sheffey A., Xian T. and Zhu *X.* (1996) *ADVANCE Evaluation: Base Data and Static Profile,* Urban Transportation Center, University of Illinois, Chicago.

Urban Transportation Center (1995) *Travel Time Prediction and Performance of Probe and Detector Data: Evaluation Test Plan,* University of Illinois, Chicago.

Urban Transportation Center (1995) *Detector Travel Time Conversion and Fusion of Probe and Detector Data: Evaluation Test Plan,* University of Illinois, Chicago.

Glossary

Cycle Failure - see Signal Cycle Failure

Detector - Inductive loop detectors are deployed in the study area. These units are buried underground, within the road surface, and work on the principle that the passage of a vehicle on the road surface above causes a change in the induction of the loop.

Incident Detection (ID) - The detection at the TIC of activities on the roadway that significantly reduce the capacity of the roadway from the expected capacity at a particular time. The detection may be based on input from probes, fixed detectors, anecdotal sources, and such other data as may be available.

Mobile Navigation Assistant (MNA) - An in-vehicle navigation system designed and built by Motorola that determines vehicle position, performs route planning based on current traffic information, and provides dynamic route guidance information to the driver.

Off-Peak - that portion of the day considered to have lighter traffic flow, defined in the experiment as 1:00 pm — 4:00 pm.

Peak - that portion of the day considered to have heavier traffic flow, defined in the study as 4:00 pm — 6:00 pm.

Probe Vehicle - A vehicle equipped with the ADVANCE Mobile Navigation Assistant. The probe vehicle automatically reports travel times to the ADVANCE Traffic Information Center as it traverses the test area.

RF - Radio Frequency, the means by which probe vehicles communicate with the TIC.

Signal Cycle Failure - this happens when a vehicle arrives at a signal-controlled intersection during the red phase and waits through the whole of the following green phase without proceeding through the intersection.

Static Profile (SP) - static information of the roadway link including day type, link ID and average travel times for a specific time period.

Traffic Information Center (TIC) - Consisting of the hardware, software, a centralized facility and operations personnel. It communicates to and from probes and external systems.

Traffic Related Functions (TRF) - Subsystem consisting of data fusion, vehicle dynamics, incident detection and travel time prediction algorithms.

Travel Time Prediction (TTP) - An algorithm used in the prediction at the TIC of future short term travel times on links to develop future adjustments to the static profiles.